COMPUTER AIDED 3D SKULL - 2D PHOTO SUPERIMPOSITION FOR FORENSIC ANTHROPOLOGY

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by

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PENINDIHAN TENGKORAK 3D - FOTO 2D DENGAN BANTUAN KOMPUTER UNTUK ANTROPOLOGI FORENSIK

ABSTRAK

Pengenalpastian manusia melalui Craniofacial Superimposition (CS) atau Penindihan Kraniofasial adalah salah satu penyelidikan yang utama dalam sains forensik. Secara asasnya, CS adalah satu teknik pengimbasan forensik yang digunakan untuk mengenal pasti identiti tengkorak yang tidak diketahui melalui pemadanan dengan gambar foto individu-individu yang dilaporkan hilang. Imej muka yang diperbesarkan kepada saiz sebenar dan perihal orientasi tengkorak untuk disepadankan seperti postur dalam foto muka adalah dua masalah utama yang wujud dalam kaedah konvensional dan juga bantuan komputer. Tujuan penyelidikan ini adalah untuk mencadangkan bantuan komputer yang baru dikenali sebagai Z Terlindung bagi mengendalikan masalah-masalah tersebut. Z Terlindung dibahagikan kepada pendaftaran tengkorak 3D - foto 2D (3D-2D) dan pendaftaran tengkorak 3D - model muka 3D (3D-3D). Pendaftaran 3D-2D adalah penindihan antara tengkorak 3D dengan imej foto muka 2D dan z-koordinat (nilai kedalaman) titik 2D yang dipilih akan dianggarkan dengan menggunakan model muka min 3D untuk mengira transformasi parameter. Pendaftaran 3D-3D pula adalah kaedah pendaftaran baru dan imej foto muka 2D dibina semula kepada model muka 3D menggunakan "Simplified Generic Elastic Model" (S-GEM) yang dicadangkan dan model muka tersebut akan bertindih dengan tengkorak 3D. "Quasi-Newton Iterative Closest Point" (QN-ICP) dan "Analytical Curvature B-spline" (AC B-spline) yang mewakili titik pendaftaran dan lengkungan pendaftaran dicadangkan untuk mengenal pasti pasangan yang sepadan antara tengkorak dan muka. Eksperimen yang lebih luas telah dijalankan untuk menilai

keberkesanan cadangan yang dikemukakan dengan menggunakan data awam yang boleh didapati serta data perubatan yang sulit dan peribadi. Kaedah cadangan ini juga dibandingkan dengan kaedah lain (pelbagai) yang didapati untuk menentukan kaedah yang paling berkesan berdasarkan kadar rangkuman, kadar positif benar dan analisis kedudukan. Kadar rangkuman mewakili jumlah ketersediaan pasangan yang sepadan dalam kumpulan pencalonan dan kadar positif tulen ditentukan berdasarkan pasangan sepadan yang mempunyai kadar ralat paling rendah. Keberkesanan kaedah-kaedah tersebut juga diukur mengikut kedudukan pasangan yang sepadan dalam kumpulan pencalonan. Keputusan eksperimen menunjukkan bahawa integrasi pengetahuan antropologi forensik (imej muka yang diperbesarkan kepada saiz sebenar dan perihal orientasi) bagi parameter transformasi dalam Z Terlindung menghasilkan output yang lebih baik berbanding kaedah-kaedah konvensional. Keputusan tersebut juga menunjukkan cadangan "AC B-spline" dalam pendaftaran 3D-2D adalah kaedah yang paling berkesan dalam perbandingan dengan kaedah-kaedah lain. Ia mampu mencapai kadar rangkuman 75.86%, kadar positif benar 13.79% dan indeks kedudukan 6.02. Pemerhatian bagi penindihan (pembesaran saiz sebenar dan orientasi) di antara data tengkorak 3D dan imej foto muka 2D (atau model muka 3D) menggunakan Z Terlindung juga telah dijalankan dan output tersebut turut menunjukkan hasil yang memuaskan di mana saiz dan orientasi tengkorak 3D dengan imej foto muka 2D adalah selaras antara satu sama lain.

COMPUTER AIDED 3D SKULL - 2D PHOTO SUPERIMPOSITION FOR FORENSIC ANTHROPOLOGY

ABSTRACT

Identification of humans via Craniofacial Superimposition (CS) is one of the prominent research areas in forensic science. Basically, CS is a forensic imaging technique used to identify an unknown skull by matching it with the available face photographs of missing individuals. Life-size enlargement of the face image and orientating the skull to correspond to the posture seen in the face photograph are the two main problems that exist in the conventional as well as in the computer-aided CS. This research is to address these two potential issues by proposing a new computer-aided approach known as Hidden-Z. In the thesis, Hidden-Z approach is divided into 3D skull - 2D photo registration (3D-2D) and 3D skull - 3D face model registration (3D-3D). The 3D-2D registration is the superimposition between the 3D skull and the 2D face image where the z-coordinate (depth value) of the selected 2D feature points are estimated using a 3D mean face model to compute the transformation parameters. The 3D-3D registration is a new registration method where the 2D face image is reconstructed to 3D face model using the proposed Simplified Generic Elastic Model (S-GEM) and the face model is superimposed with the 3D skull. Quasi-Newton Iterative Closest Point (QN-ICP) and Analytical Curvature B-spline (AC B-spline) which represent the point registration and curve registration are proposed to identify the corresponding pairs between the skulls and the faces. Extensive experiments were conducted to evaluate the effectiveness of the proposed methods using the publicly available datasets and also the private and confidential medical datasets. They were also compared with various available methods to determine the most effective approach

based on inclusion rate, true positive rate and ranking analysis. The inclusion rate represents the availability of the corresponding pairs in the probable group and the true positive rate is determined based on the corresponding pairs with the lowest error among the matching pairs. The ranking of the corresponding pairs is also computed in order to evaluate the effectiveness of the methods. The experimental results show that the integration of forensic anthropology knowledge (life-size and orientation) for computing the transformation parameters in the Hidden-Z approach, produces better outputs than the conventional methods. The results demonstrated that the 3D-2D registration using proposed AC B-spline is the most effective method compared to the other methods where it is able to achieve 75.86% of inclusion rate, 13.79% of true positive rate and 6.02 of ranking index. Observation of the superimposition (life-size enlargement and orientation) between the 3D skull and the 2D face photo (or 3D face model) of the data using Hidden-Z is also carried out and the outputs are also showing satisfied results where the size and the orientation of the 3D skulls and the 2D face photos are well aligned with each other.

CHAPTER 1

INTRODUCTION

An introduction of the forensic anthropology is introduced to the reader in this chapter where the current dissertation is focused on. Then, a short review of forensic identification by craniofacial superimposition techniques is discussed, since the main goal of the dissertation lies in the development of a new approach that intends to incorporate conditional anthropological parameters which differs from the existing approaches. Problem statements are determined based on the review and the remainder of the chapter is focused on the objectives, contributions and overview of the proposed methodology.

1.1 Background of Forensic Anthropology

Crime investigators rely on forensic science for revealing the truth and in cases requiring the establishment of the victim's identity from the human remains. Initially, the investigation will start by tracking on the exhibits such as identity card which is left around the corpse or skeleton. However, when the routine methods of identification such as the use of DNA become difficult, the forensic anthropologists who are the specialists in the human skeleton are usually summoned to identify the victims by examining the individuality of a skeleton based on the unique skeletal anomalies, pathological conditions, or evidence of acute trauma to the bone. It is likely to identify the individual when the skeletal characteristics are known.

In Malaysia, human remains buried or cremated in somewhere are retained in two hospitals of Kuala Lumpur (Hospital Kuala Lumpur and University Malay Medical Centre) and 25% of the skulls are preserved in Hospital Pulau Pinang. These death cases are confirmed to be involved in equivocal death or possible homicide and only 10% has been recognised through DNA based identification (Jayaprakash et al., 2010). According to the record of missing persons provided by the Royal Malaysian Police (PDRM) in 2010, one thousand missing individuals continued to be untraced and the number is gradually increasing through the years. Besides, lack of dental information and other pertinent data such as fingerprints are common problems in South East Asian countries including Malaysia. It is perceived when the Tsunami struck on 26 December 2004 and caused 217,000 deaths (and also approximately 125,000 injured) in over many countries including Malaysia, Thailand, Myanmar, Bangladesh, India, Sri Lanka, the Maldive and Seychelle Islands, and the East African coast of Tanzania, Kenya and Somalia (James et al., 2005). In Thailand, for most of the western victims, 85.5% were identified using dental records and 0.4% using DNA prompting. For the Thai locals, there are still 73% of the victims remained unidentified until 2006 due to the lack of dental records and high cost of applying DNA techniques (Sribanditmongkol et al., 2007). Under such circumstances, implementation of facial reconstruction or craniofacial superimposition is necessary for identifying the human remains. The approaches are the two common techniques that have been developed and evolved over the centuries.

1.1.1 Facial Reconstruction

In face reconstruction, the face of the victim is restored based on the skull using clay by forensic anthropologists (Taylor, 2000). With all the experiences and knowledge that the experts possess, they will estimate and make assumption on the thickness of the soft tissues of the victim based on the exhibits. For example, if the shirt found at the crime scene is outsized, positively, the victim might be a big size person. With that, assumption markers that indicate thickness of the soft tissues will be placed on the skull as shown in Figure 1.1a. In order to simulate the face, structure of

(a) Skulls with markers (b) Covered with muscles (c) Complete face

Figure 1.1: The Facial reconstruction referred from Simon Sudbury.
(a) Skulls with markers (tissue thickness); (b) Covered with muscles; (c) After restoration process. (http://simonofsudbury.weebly.com/3-dimensional-clay-facial-reconstruction.html).

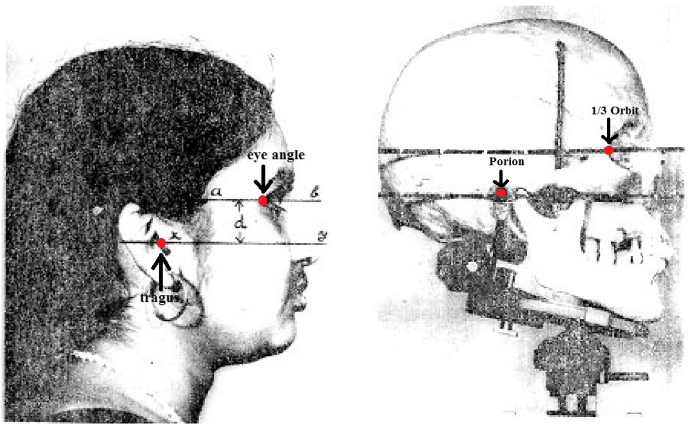
the muscles are added on the skull as shown in Figure 1.1b. Figure 1.1c shows the complete appearance of the skull after the restoration process. The restoration process is done manually by the forensic anthropologists which requires more than two weeks to restore a single skull. Hence, automatic facial reconstruction using computer-aided techniques are developed (Vanezis et al., 1989; Quatrehomme et al., 1997; Tu et al., 2005; Paysan et al., 2009) in order to reduce the time from the complicated process. However, there are difficulties in the computer-aided approaches such as the prediction of thickness of the soft tissues for the facial features which requires complex calculations. Craniofacial superimposition is preferable compared to facial reconstruction especially when the size of the samples are extremely large as occurred in Tsunami cases.

1.1.2 Craniofacial Superimposition

Craniofacial superimposition is the identification process of a skull image superimposed with a face image for determining the correspondence between them. The earliest technique applied for superimposition was called photographic superimposition and it was first applied in crime investigation on Ruxton's case in the year 1935 as shown in Figure 1.2. The skull recovered was independently oriented to the same posture as the heads in the portraits by trial and error method that also considered the angulation of physical objects in the portraits. Subsequent authors such as Sen (1962) and Basauri (1967) have also oriented the skull by a similar trial and error process using frontal landmarks. Sekharan (1971) improved the method by using the objects in the images for obtaining 'life-size' enlargements of face images. Life-size enlargement is the scaling adjustment between the face image and the skull where the size of the skull must be correlated with the size of the face image in any reasonable enlargement (Jayaprakash et al., 2001). Furthermore, Sekharan (1973) prescribed a scientific method for achieving appropriate orientation of the skull in relation to posture of the face by using the vertical relationship 'd' distance between eye angle and tragus (ear) seen in a life-size face image as shown in Figure 1.3.

While the use of life-size images was emphasized by the other authors such as Dorion (1983), Mckenna et al. (1988) and Maat (1989), the use of eye angle and tragus relationship had not been mentioned. In 1993, Sekharan (1993) prescribed the use of Whitnall's tubercles instead of the lower 1/3 distance in the orbit suggested earlier (Sekharan, 1971). However, the method suggested for preparing the life-size enlargement continued to be based on the measurements of physical objects prescribed

Figure 1.2: The output of photographic superimposition between the portrait of Mrs. Ruxton and her skull.



(a) Lateral view of the face (b) Lateral view of the skull

Figure 1.3: Appropriate orientation between skull and face measured using 'd' distance by Sekharan (1973). (a) Lateral view of the 'd' distance on the face (b) Lateral view of the 'd' distance on the skull.

earlier. Whitnall's tubercle could be easily located as it protrudes from the surface along the inner orbital margin as shown in Figure 1.4.

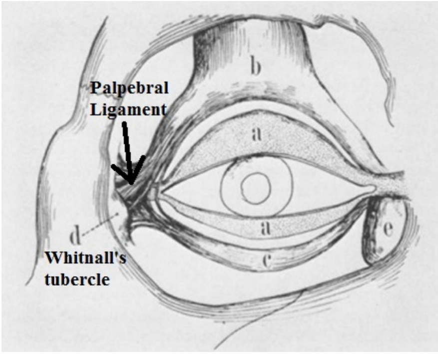


Figure 1.4: The illustration of Whitnall's tubercles by Stewart (1983). Whitnall's tubercle is labeled as 'd' in the figure.

During the latter part of 1970s, Helmer and Gruner (1977), Hagemeier (1983), Yoshino (1995; 1997) and and Clement and Ranson (1998) introduced the video superimposition method that acquired popularity replacing the photographic method. In the video process, two video cameras were used, one for the face image and the other for the skull as shown in Figure 1.5. The size of the face image and the posture

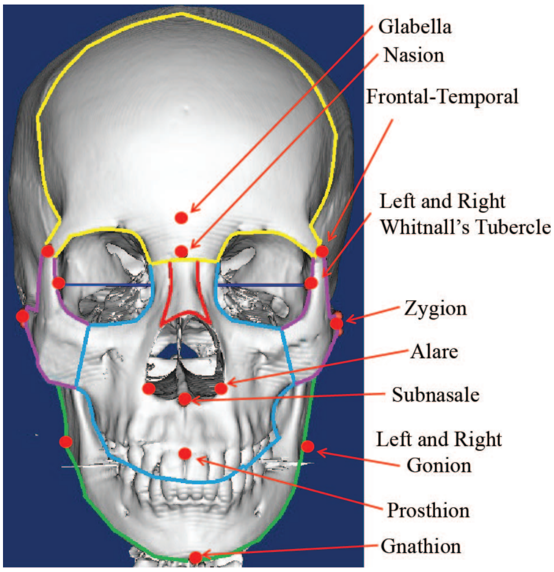
Figure 1.5: Setup of the equipments of video superimposition which located at the Health Campus of Universiti Sains Malaysia.

of the skull were adjusted on a real time basis using a vision mixing device from which the images were cast on a television monitor. However, the authors reporting the use of video method have highlighted only on life-size adjustment while orientation of the skull continued to be on trial error basis. In 1994, Austin-Smith and Maples (1994) who verified the reliability of the video superimposition method considered the tissue thickness using tissue depth markers for adjusting the size and posture of the skull. The authors have considered approximating the orientation of the skull using the distance between the lateral angle of the eye and tragus in the face image. However, they have not used life-size enlargements since the monitor used by them was a 14 inch cathode ray tube. Iten (1987) and Jayaprakash et al. (2001) have emphasized the important elements in cranio-facial superimposition, one, obtaining the relative enlargement and the other, appropriate orientation of the skull. The technique of orientation described by Sekharan (1973; 1993) and Jayaprakash et al. (2001), is shown emphasized by Fenton et al. (2008) although the size of the images in life-size was adjusted based on the size of the face image displayed on the monitor screen.

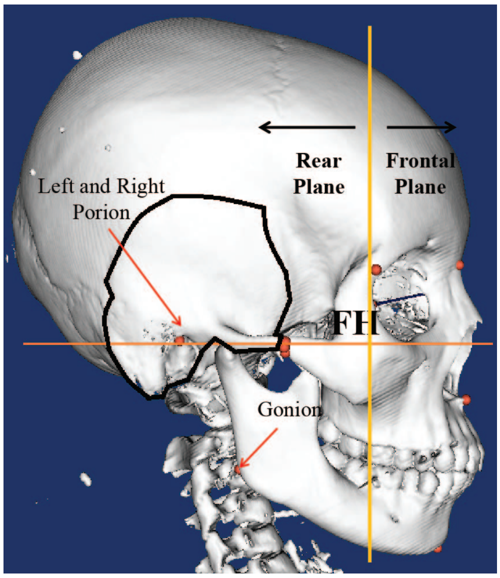
The application of computers in craniofacial superimposition can be categorized into two types, first, software such as Photoshop or Coral Draw as an additional aid while still achieving the skull-face overlay manually and the other computerized or computer based processes that aim at automating the overlay process itself. Matsui (2001) overlaid the skull image with the face image using the layer function in Photoshop. Vertex, nasion, subnasale, stomion, gnathion, zygion, endocanthion, exocanthion and alare (as shown in Figure 1.6 and Figure 1.7) were marked on both the images and were used for examination. Bilge et al. (2003) and Ricci et al. (2006) also used Photoshop or other software although the landmarks and adjustment methods used differed. In 2012, Gordon and Steyn (2012) used the 3D Studio Max software for achieving the overlay to determine the reliability of the skull-photo superimposition technique in South Africa legal system. Nasion, subnasale, and ectocanthions (as shown in Figure 1.7) were respectively assigned to the skull and face photographs and were used for orienting the skull to correspond to the posture of the face in the photograph.

Computer based superimposition was first proposed by Nickerson et al. (1991) in 1991. Landmarks such as ectocanthions, glabella, nasion and subnasale (as shown in Figure 1.7) were selected to calculate the affine and perspective transformation (rotation, scaling and translation) to map the 3D-skull mesh and its landmarks to the 2D landmarks in the face using real-coded genetic algorithms (RCGA). In 2007, Ballerini et al. (2007) suggested similar technique to Nickerson et al. (1991) in order to compute the transformation parameters. Ibáñez et al. (2008; 2009a) improved the computation by determining the proper position of the landmarks using fuzzy landmarks. Covariance matrix adaption evolution strategy (CMA-ES) that related to maximum likelihood was used for superimposition to register between the skull and the face by Santamaria et al. (2009). It was further enhanced by Ibáñez et al. (2011) using weighted and fuzzy-set-theory-based landmarks to compute the fitness function. In 2009, Ibáñez et al. (2009c) implemented the superimposition with RCGA, CMA-ES and binary-coded GA(BCGA). Multi-modal GA (Ibáñez et al., 2009b) was also proposed where limited resources was shared to the elites of the sub-populations which had the similarities. The purpose was to preserve the best individuals and re-arrange the other member of the sub-populations. In 2012, a cooperative Co-Evolutionary Approach (CEA) (Ibáñez et al., 2012) dealing with the skull-face overlay uncertainty was proposed. Skull was adjusted to the same posture as the face in the photograph using certain landmarks in a common coordinate frame. The work was further improved by considering the imprecise location of landmarks and also the imprecise spatial correspondence between cranial and facial landmarks (Campomanes et al., 2014, 2015a, 2016). A decision support system (Campomanes et al., 2015b,c) was designed to identify the matching pair based on certain criteria such as the outlines of the skull and the face. Chain code was used to calculate the spatial correspondence (outlines) between the bony of the skull and the chin of the face.

It is likely that the superimposition process is guided by specific anthropometrical landmarks located in both the skull and the photograph of the missing person where the thickness of the soft tissue is low. The typically used skull landmarks is shown and described in Figure 1.6 and Table 1.1.



(a) Frontal view of the skull



(b) Lateral view of the skull

Figure 1.6: Craniometric landmarks.

Table 1.1: Description of the skull landmarks (also known as craniometric landmarks) (Panizo et al., 2010; Farkas, 1981a; Stewart, 1983)

Landmark	Position (Plane)	Description
Frontal-Temporal(FT)	Frontal	Lateral point of junction of the frontal (Fb) and zygomatic bones (Zb)
Glabella(Gl)	Frontal	Prominent point between the supraorbital ridges in the midsagittal plane
Gnathion(Gn)	Frontal	A midway point between the most anterior and most inferior points on the chin
Gonion(Go)	Rear	Most lateral point at the mandibular (Mb) angle
Nasion(N)	Frontal	Midpoint of the suture between the frontal (Fb) and the two nasal bones (Nb).
Porion(po)	Rear	Most lateral point on the roof of the external auditory meatus (EaM)
Prosthion(Pro)	Frontal	Apex of the alveolus in the midline between the maxillary (MaB) central incisor
Whitnall's Tubercle(Wt)	Frontal	The orbital surface of the frontal process of the zygomatic bones (Zb), just within the orbital margin
Zygion(Zy)	Rear	Most lateral point on the zygomatic (Zb) arch

Fb : Frontal bone as highlighted with yellow curve in Figure 1.6a;
Zb : Zygomatic bones as highlighted with purple curve in Figure 1.6a;
Mb : Mandibular bone as highlighted with green curve in Figure 1.6a
Nb : Nasal bone as highlighted with red curve in Figure 1.6a;
EaM : Position of external auditory meatus as highlighted with black curve in Figure 1.6b;
MaB : Maxillary bone as highlighted with blue curve in Figure 1.6a.

Meanwhile, the typically used face landmarks is shown and described in Figure 1.7 and Table 1.2.

Table 1.2: Description of the skull landmarks (also known as craniometric landmarks) (Panizo et al., 2010; Farkas, 1981a).

Landmark	Position (Plane)	Description
Alare(Al)	Frontal	Most lateral point on the alar contour
Exocanthion(ex)	Frontal	Point at the outer commissure of the eye fissure
Glabella(gl)	Frontal	Most prominent point in the midline between the eyebrows
Gnathion(gn)	Frontal	Point on the soft tissue chin midway
Gonion(go)	Rear	Most lateral point of the jawline at the mandibular angle
Nasion(n)	Frontal	Point of maximum concavity between the nose and forehead in the midline
Subnasale(sb)	Frontal	Midpoint of the columella base at the angle where the lower border of the nasal septum meets the upper lip
Tragion(tr)	Rear	Notch on the upper margin of the tragus

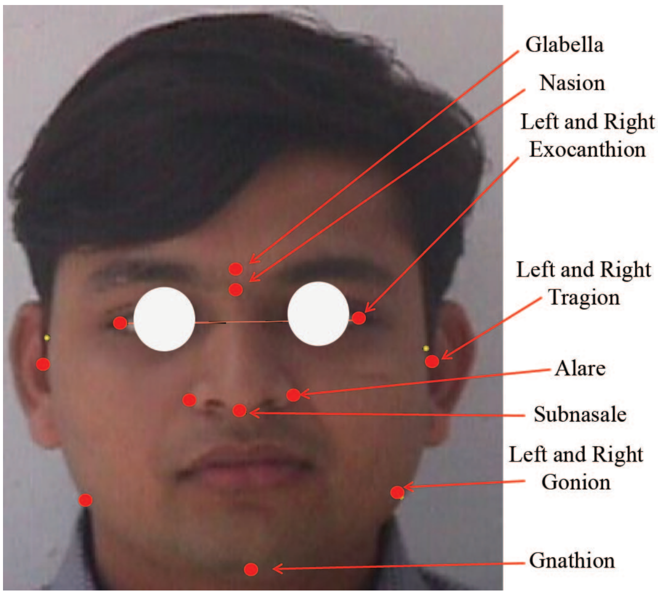


Figure 1.7: Cephalometric landmarks with the frontal view of the face.

These landmarks are located on two different planes (frontal and rear) of the skull and face as shown in Figure 1.7. Besides, based on the brief discussion of the background, two important common operations have to be done: 1) life-size enlargement which refers to the scaling adjustment between the face image and the skull; and 2) orientation which refers to the posture adjustment of the skull to correspond with the face image. These attributes including the position of the landmarks of every technique in the photographic superimposition, video superimposition and computer-aided superimposition are listed down in Table 1.3, Table 1.4, and Table 1.5 .

Table 1.3: Summary of the photographic superimposition on the life-size, orientation and position of the landmarks.

	Life-size	Orientation	Landmarks' Position
Glaister and Brash (1937)	✓	×	×
Sen (1962)	✓	×	Frontal plane
Basauri (1967)	✓	×	Frontal plane
Sekharan (1971; 1973; 1993)	✓	✓	Frontal plane and rear plane
Dorion (1983)	✓	×	Frontal plane and rear plane
Mckenna et al. (1988)	✓	×	×
Maat (1989)	✓	×	×
Reddy (1973)	×	×	-

Table 1.4: Summary of the video superimposition on the life-size, orientation and position of the landmarks.

	Life-size	Orientation	Landmarks' Position
Helmer and Gruner (1977)	✓	×	-
Hagemeier (1983)	✓	×	-
Iten (1987)	×	✓	-
Yoshino et al. (1995; 1997)	✓	×	Frontal plane
Austin-Smith and Maples (1994)	×	✓	Frontal plane and rear plane
Clement and Ranson (1998)	✓	✓	-
Jayaprakash et al. (2001)	✓	✓	Frontal plane and rear plane
Fenton et al. (2008)	×	✓	Frontal plane

Table 1.5: Summary of the computer-aided superimposition on the life-size, orientation and position of the landmarks.

	Life-size	Orientation	Landmarks' Position
Nickerson et al. (1991)	×	×	Frontal plane
Matsui (2001)	×	×	Frontal plane
Bilge et al. (2003)	×	×	-
Ricci et al. (2006)	×	×	Frontal plane
Gordon and Steyn (2012)	×	×	Frontal plane
Lucia et al. (2007)	×	×	Frontal plane
Ibáñez et al. (2008; 2009a; 2009c; 2009b; 2011; 2012)	×	×	Frontal plane
Santamaria et al. (2009a; 2009)	×	×	Frontal plane
Campomanes et al. (2014 2015a; 2015b; 2015c; 2016)	×	×	Frontal plane

Based on the tables, these superimposition approaches (especially computer-aided superimposition) are found to have common problems which lead to the problem statements in Section 1.2.

1.2 Problem Statement

Determination of a suitable computer-aided superimposition approach which includes all the attributes (as indicated in Table 1.3, Table 1.4, and Table 1.5) is the main problem of the thesis. It is a controversial issue for this research which is what kind of approaches should be implemented into the superimposition. Evolutionary algorithms such as genetic algorithm (GA) (Nickerson et al., 1991; Ballerini et al., 2007; Ibáñez et al., 2009a; Campomanes et al., 2015b) and neural network (NN) (Nandy and Ben-Arie, 2000, 2001) have been proposed to solve the cases. However, the techniques applied by all the mentioned approaches are found to have three sub-problems described in the next subsections.

Hence, it is a topic worthy of investigation on the suitable approach to be implemented in computer-aided craniofacial superimposition in order to produce satisfactory results.

1.2.1 Alignment Between Face and Skull

Alignment between the 2D face image and the 3D skull is one of the crucial steps in craniofacial superimposition. It is a challenging task because the representation of the face image and the skull are in different dimensions. Besides, the attributes listed in Table 1.3, Table 1.4, and Table 1.5 indicate that the existing approaches especially computer-aided superimposition have failed to use life-size enlargement and achieved anatomically appropriate orientation of the skulls. Transformation parameters including scaling, rotation and translation are computed using the selected feature points from the 2D face image and the 3D skull respectively, so that the size and the posture between the face image and the skull are relatively fitted with each other. Alignment is an important procedure in the superimposition where false positive matches should be strictly avoided as it might affect the judgments of the practitioner. False positive happens when the subject of the 2D face image does not belong to the skull but it corresponds well with the skull.

1.2.2 Selection of landmarks

The second sub-problem is the selection of proper landmarks that has not been addressed by the authors of the existing computer-aided approach (Nickerson et al., 1991; Ricci et al., 2006; Ghosh and Sinha, 2001; Gordon and Steyn, 2012). Anatomically related or homologous landmarks on the face and the skull in two different locations, viz. front and rear planes, were not selected and used during the process of orienting the skull. Only the landmarks on the frontal (eye) plane had been selected and implemented as shown in Table 1.5. Santamaría et al. (2009b) discussed the coplanarity problem in forensic craniofacial superimposition. Two case studies with different phenomenon were included. Approximately six to sixteen coplanar (frontal) landmarks were selected to estimate the transformation and perspective projection parameters using GA.

Postulation of sole reliance on the landmarks in the front plane of the face to orient the skull would lead to arbitrary tilting of the skull model to fit a face image and thus may lead to false positives (Santamaría et al., 2009b). A true positive can only be determined when the skull is appropriately oriented to correspond to the posture in the face image. True positive happens when the subject of the 2D face image is confirmed to belong to the skull. Hence, selection of the proper landmarks is a crucial matter in craniofacial superimposition. The choice of the corresponding anatomical landmarks on the face and the skull needs to be decided properly. The final output of the alignment and also the registration rely heavily on the selection of the landmarks.

1.2.3 Registration Between Face and Skull

Registration in craniofacial superimposition is an important step to determine the correspondence between the face and the skull. It is a difficult task because the appearance between the subjects varies from each other. Naturally, neither the features (viz., nose, mouth, eyes or ears) on the face nor the features on the skull can be used for matching. The outline of a face is totally different from his or her skull because the skull is covered with soft tissues. Hence, areas that can be measured for registration are limited. Chain code has been proposed by Campomanes et al. (2015b; 2015c) to determine the matches between the face and the skull. However, chain code is sensitive to noise due to the variation of the shapes. A prudent decision must be made for the selection of area and also the techniques of the registration to avoid false positive results.

1.3 Research Objectives

The main objective of this research is to overcome the problems of the existing computer-aided superimposition by proposing an effective approach. The new computer-aided approach is integrated with the conditional parameters such as life-size enlargement, orientation and also selection of the proper landmarks. This can be further subdivided into the following:-

1. To resolve the alignment issues that is inherent between the skull and the face using the proposed approach by incorporating appropriate forensic knowledge;
2. To define the potential non-coplanar landmarks to compute the life-size enlargement and orientation of the alignment between the skull and the face;
3. To determine the point registration and curve registration methods that able to determine the match between the skull and the face.

1.4 Research Contributions

The main contribution of the thesis is the proposal of Hidden-Z approach which varies from the existing evolutionary approaches in computer-aided superimposition. It is a new approach which obtains the z-coordinate (assumed hidden) of the feature points (2D images) and integrates with the forensic anthropology knowledge to solve the alignment and the registration problems. All of the selected corresponding feature points between the 3D skull and the 2D face images of the alignment process are non-coplanar landmarks as suggested by Jayaprakash et al. (2001). The additional contributions are listed as follows:

1. The 3D skull - 2D face image registration method in Hidden-Z approach. The z-coordinate of the selected 2D feature points (from the 2D face image) are computed using a 3D mean face model in order to estimate the transformation parameters for x, y and z dimensions;

2. The 3D skull - 3D face model registration method in Hidden-Z approach. The 2D face image is reconstructed to 3D face model using the proposed Simplified Generic Elastic Model (S-GEM). It is to improve the alignment problem between the skull and the face and provide the lateral view of the superimpositions;

3. Analytical Curvature B-spline (AC B-spline) in the curve registration method to determine the correspondence between the skull and the face;

4. Quasi-Newton Iterative Closest Point (QN-ICP) in the point registration method to determine the correspondence between the skull and the face.

1.5 Overview of the Methodology

In this thesis, following the conceptual basis used for orienting the skull in the photographic and video superimposition, Hidden-Z approach is proposed. The proposed method emphasizes adherence to two important parameters: 1) maintaining the life-size of the face image in relation to the size of the skull termed and 2) orienting the skull on an anthropological basis. The approach has been divided into two different main registrations for the craniofacial superimposition: 1) 3D skull - 2D face registration (3D-2D) and 2) 3D skull - 3D face model registration (3D-3D). The purpose of both registrations is to obtain the z-coordinates of the 2D face images (or the 2D feature points) in order to solve the alignment and the registration problems. Figure 1.8 shows the overall flow of the proposed craniofacial superimposition and the tasks of each stage is represented with the letters. Quantitative evaluations and qualitative observations will be carried out at the decision making stage. In this section, a brief methodology is explained in the following sub-sections and the detail will be further explained in Chapter 6.

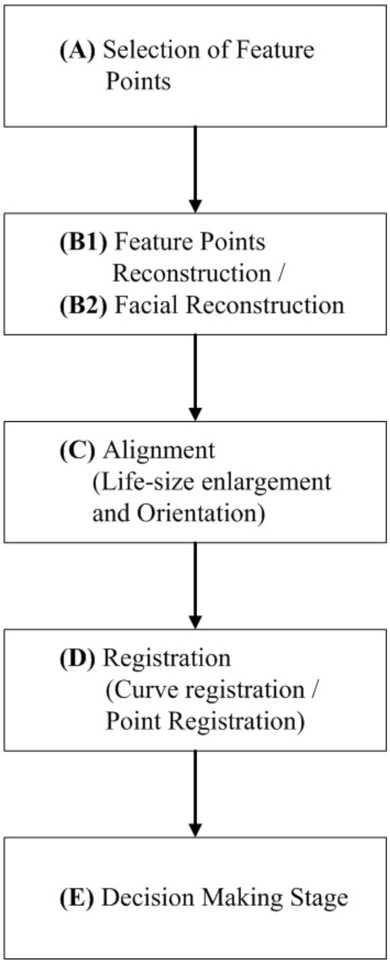


Figure 1.8: Flowchart of the Hidden-Z approach deployed by the craniofacial superimposition technique where each stage is represented with a letter.

A : Selection of the corresponding landmarks;

B1: Reconstruction of the selected feature points in 3D-2D where the *z*-coordinates of certain feature points are estimated;

B2: Reconstruction of 2D face image in 3D-3D where the 3D face model of the input 2D face image is reconstructed;

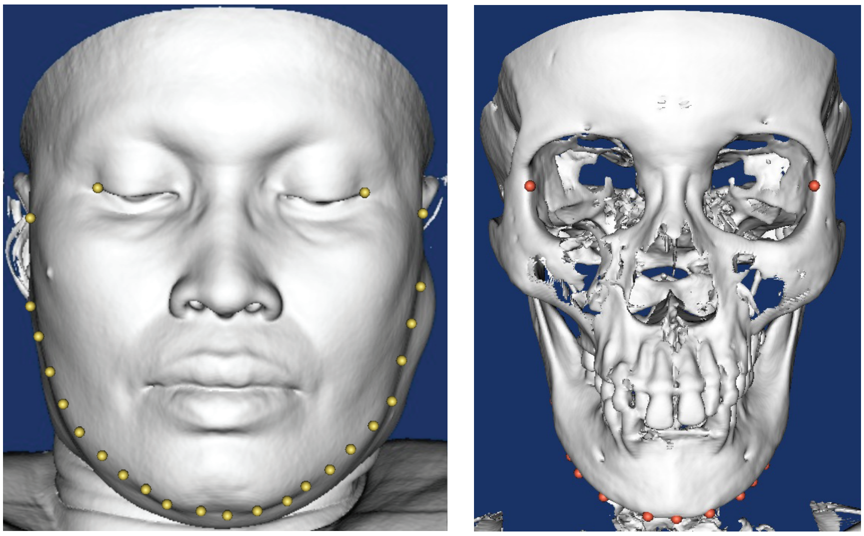
C : Alignment (life-enlargement and orientation);

D : Registration process to determine the corresponding pair;

E : Decision making stage to evaluate the outputs.

1.5.1 3D Skull - 2D Face Registration

Initially, a set of corresponding landmarks (as shown in Figure 1.9) between the skull and the face is chosen (Figure 1.8(**A**)). By the conceptual basis of forensic anthropology, four important anatomical landmarks (Whitnall's tubercle, exocanthion, porion and tragion) which exist in the chosen set are used to compute the transformation parameters to perform the alignment (Figure 1.8(**C**)). But the z-coordinate of the anatomical landmarks must be estimated using a 3D mean face model before the alignment process (Figure 1.8(**B1**)). Point registration (QN-ICP) and curve registration (AC B-spline) are carried out separately using the landmarks around the jawline of the skull and the face (Figure 1.8(**D**)). Lastly, these registration techniques are evaluated and compared with other available methods based on the outputs of the superimposition. A decision making stage based on the inclusion rate and true positive rate is implemented at the end of the process to determine the corresponding matches based on the outputs of the registration (Figure 1.8(**E**)).



(a) (b)

Figure 1.9: The selection feature points for transformation on the (a) 2D face image and the (b) skull.