VOT 71905

THE DESIGN AND DEVELOPMENT OF A PROTOTYPE NON-CONTACT MEASUREMENT SYSTEM FOR CRANIOFACIAL SURGERY

REKABENTUK DAN PEMBANGUNAN PROTOTAIP SISTEM PENGUKURAN TANPA SENTUH UNTUK PEMBEDAHAN KRANIOFASIAL

ZULKEPLI MAJID
HALIM SETAN
KOON FOOK CHONG

RESEARCH VOTE NO: 71905

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FAKULTI KEJURUTERAAN & SAINS GEOINFORMASI
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THE DESIGN AND DEVELOPMENT OF A PROTOTYPE NON-CONTACT MEASUREMENT SYSTEM FOR CRANIOFACIAL SURGERY

Vote No: 71905

2. **PROJECT LEADER** :

Name : ZULKEPLI BIN MAJID

Address : FACULTY OF GEOINFORMATION SCIENCE AND ENGINEERING, UTM

Tel : 07 5530829 Fax : 07-5566163 e-mail : zulkepli@fksg.utm.my

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a) APPROVED FUNDING RM : …………………………

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7. TECHNICAL DESCRIPTION AND PERSPECTIVE

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a) Technology Description

b) Market Potential

c) Commercialisation Strategies

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8. RESEARCH PERFORMANCE EVALUATION

a) FACULTY RESEARCH COORDINATOR

	Excellent	Very Good	Good	Satisfactory	Fair	Weak
Research Status	( )	( )	( )	( )	( )	( )
Spending	( )	( )	( )	( )	( )	( )
Overall Status	( )	( )	( )	( )	( )	( )

Comment/Recommendations :

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Overall Status	( )	( )	( )	( )	( )	( )

Comments :-

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Recommendations :

☐ Needs further research

☐ Patent application recommended

☐ Market without patent

☐ No tangible product. Report to be filed as reference

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THE DESIGN AND DEVELOPMENT OF A PROTOTYPE NON-CONTACT MEASUREMENT SYSTEM FOR CRANIOFACIAL SURGERY

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ABSTRACT

The design and calibration procedures of a new craniofacial soft tissue imaging system are developed. The designed procedures of the system are based on the integration of stereophotogrammetry and three-dimensional laser scanning techniques to capture high resolution stereo images and three-dimensional surface model of craniofacial morphology, respectively. The stereophotogrammetric technique introduced a new multi-camera system consisting of eight high resolution digital cameras, high speed shutter synchronisation controller and a specially built patient's chair with photogrammetric control frame. The *novel technique* dubbed as "natural features technique" is developed and examined to improve the accuracy of craniofacial landmarks measurements via captured stereo images. The laser scanning system consists of two high resolution Minolta Vivid 910 laser scanners. The important factor of using the scanner for craniofacial mapping is completely tested. Finally, the registration accuracy of the point clouds datasets captured from the laser scanners is improved by using photogrammetric targets that setup on the photogrammetric control frame. Both imaging systems are calibrated independently using special built camera calibration test field (to calibrate the camera system) and calibrated test objects (to calibrate the laser scanning system). The results show that the developed *novel technique* achieves an accuracy of 0.6mm at one standard deviation. The registration of point clouds datasets by using photogrammetric targets achieves an accuracy of less than 0.3mm at one standard deviation. The results also show that the use of laser scanning system for craniofacial mapping depends on several significant factors such as scan distance, camera focal length, laser beam intensity, scanning resolution, convergence angle and the number of overlapping scans. As a conclusion, the developed imaging system is a unique system for capturing craniofacial soft tissue datasets as the system captured various datasets (stereo images and three dimensional surface model) when the patient sits at the patient's chair with the head placed at the middle of the photogrammetric control frame.

ABSTRAK

Prosedur rekabentuk dan kalibrasi bagi sistem pengimejan tisu lembut kraniofasial telah dihasilkan. Prosedur rekabentuk sistem di atas adalah berasaskan integrasi teknik fotogrametri stereo dan pengimbasan laser tiga dimensi untuk mengutip imej stereo berresolusi tinggi dan model tiga dimensi morpologi kraniofasial. Teknik fotogrametri stereo memperkenalkan sistem multi-kamera yang baru yang mengandungi lapan kamera digital berresolusi tinggi, alat kawalan kamera berkelajuan tinggi dan kerusi pesakit yang dibuat khas yang dilengkapi dengan bingkai kawalan fotogrametri. Satu *teknik novel* dikenali sebagai "teknik bahagian muka natural" dihasilkan dan diuji untuk menambahbaik ketepatan pengukuran titik-titik kraniofasial menggunakan imej stereo. Sistem pengimbasan laser mengandungi dua alat pengimbasan laser Minolta Vivid 910 yang berresolusi tinggi. Faktor-faktor penting yang mempengaruhi ketepatan penggunaan alat pengimbasan laser tersebut telah diuji sepenuhnya. Akhirnya, ketepatan registrasi data-data yang dikutip menggunakan alat pengimbasan laser ditambahbaik dengan menggunakan sasaran-sasaran fotogrametri yang disediakan di atas bingkai kawalan fotogrametri. Kedua-dua sistem dikalibrasi secara individu dengan menggunakan lapangan kalibrasi (untuk kalibrasi kamera) dan objek ujian yang dikalibrasi (untuk kalibrasi alat pengimbasan laser). Hasil menunjukkan bahawa *teknik novel* yang dihasilkan memberikan ketepatan 0.6mm bagi pengukuran titik-titik kraniofasial pada satu sisihan piawai. Registrasi data-data laser menggunakan sasaran-sasaran fotogrametri mencapai ketepatan kurang 0.3mm pada satu sisihan piawai. Hasil juga menunjukkan bahawa penggunaan sistem pengimbasan laser untuk pemetaan kraniofasial bergantung kepada beberapa factor seperti jarak imbasan, jarak fokal kanta, ketumpatan laser, resolusi imbasan, sudut tumpu dan bilangan tindihan imbasan. Sebagai penutup, sistem pengimejan yang dihasilkan adalah unik untuk kutipan data-data tisu lembut kraniofasial kerana sistem tersebut mengutip lebih dari satu data (imej stereo dan model tiga dimensi kraniofasial) apabila pesakit duduk di kerusi dengan bahagian kepala pesakit diletakkan di tengah-tengah bingkai kawalan fotogrametri.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Introduction

Close-range photogrammetry is a method for obtaining spatial information of an object where the distance between the cameras to the object is less than 100 meters and cameras are positioned close to the object (*Cooper and Robson, 1996*). Close-range photogrammetric method has been used in many fields such as architectural, industrial and medical applications. In medical application (namely Medical Photogrammetry or Biostereometric), the features of human body are captured to obtain distance, angle, volume and shape. The anthropometric of the torsos, heads, faces, limbs, breasts, feet, skin, eyes and teeth are some of the interesting examples (*Newton and Mitchell 1996*). In many cases of medical photogrammetry, the human faces are the most popular part of the human body to be recorded and measured. The craniofacial anthropometric data are measured and used by surgeons to normalise the patient's faces. The same data is used by surgeons to make plans for surgical craniofacial reconstruction (pre-surgery) and to monitor the progress after the surgery (post-surgery). Close-range photogrammetry involves two types of methods, namely (a) stereophotogrammetry and (b) convergent photogrammetry. For the purpose of measuring craniofacial, both methods are used by the researchers.

Laser scanning system, which is also based on photogrammetric principle, has become a practical technology to capture 3D spatial data of an object. This system comprises of two sensors, namely laser and a CCD camera mounted in a proper casing, where the distant between them was fixed. The triangulation method was used to calculate the three-dimensional coordinate of point clouds. The laser scanning system is widely used in the measuring of craniofacial soft tissue. Subsequently, the 3D model is superimposed with a three-dimensional CT-scanned skull model for scientific surgical planning task. The computerised tomography (CT) scan as well as the Magnetic Resonance Imaging (MRI) scan can also be used to capture the craniofacial soft tissue data but due to the high scanning radiation, both modalities were only used to scan patients with craniofacial disorders or people with headache, which require the analysis of the brain. There is a number of laser scanners on the market, but for the purpose of craniofacial measurement, only the eye-safe and high speed laser scanner is needed. This is because most of the craniofacial analysis (craniofacial anthropometry) involve measurements with the eyes opened. The high speed laser scanner is highly needed when scanning the infant or young child, where they cannot remain seated for a longer period during data collection.

For the purpose of the improvement of geometry, accuracy and visual quality of 3D craniofacial spatial data, the integration between two or more craniofacial imaging modalities is required. Although the sensors are designed with modern computerized technology, there is still a limitation in capturing the 3D surface which will contribute some errors or noises in the 3D data. For example, most of the sensors that are involved with laser will have a problem when scanned on the dark surfaces of the facial area such as eye brow, beard and eye ball which are important parts of craniofacial area. Current craniofacial imaging equipments such as stereophotogrammetry, laser scanning, and Moiré scanning are considered as soft tissue data collection sensors and computerized tomography (CT) scan, Magnetic Resonance Imaging (MRI) scan and 3D digital x-ray capture mainly the hard tissue data. Among the methods for capturing the craniofacial soft tissue, stereophotogrammetry which is based on normal digital images as raw data, showed to be the most practical method for modeling of craniofacial surface. In terms of high accuracy and fast 3D surface generation, laser scanning seemed to be the best for craniofacial modeling. The problem occurred when scanning the dark surfaces on the facial surface such as the hair, eye brow, etc. On the other hand stereophotogrammetry was free from such problem. So, the integration between the two methods is highly essential for fast and accurate 3D modeling and measurement of craniofacial surface.

This study introduces new methods of acquiring, calibrating and evaluating craniofacial spatial data for the purpose of craniofacial database development for craniofacial reconstruction surgery in Malaysia. The Malaysian craniofacial database was initiated to provide a comprehensive set of craniofacial spatial data for all the racial groups, for both corrective and reconstructive surgeries. Malaysia has a large number of ethnic groups and tribal subgroups. To populate the database with the craniofacial data of all racial groups massive resources are required. Consequently, the ethnic Malay group was selected for the initial stage of the research. In the subsequent stages, more ethnic groups were included in the database.

The craniofacial spatial data acquisition system involved two types of data capturing sensors, namely (a) stereophotogrammetric cameras and (b) laser scanners. It also involved the study of the reliability, accuracy and error detection of both sensors. The needs of this research are high prioritised because high accuracy measurements of anthropometric data and three-dimensional model of craniofacial morphology are essential for modern computerized surgical techniques. The research also involved the integration of both stereophotogrammetry and laser scanning datasets to develop high accuracy and complete craniofacial surface model.

1.2 Statement of Problems

There is a need to provide a state-of-the-art surgical planning system for craniofacial reconstruction in the public hospitals in Malaysia. The surgical planning system consists of several elements; craniofacial database, craniofacial spatial data, the planner tools and modelling. The craniofacial spatial data is one of the most important elements. Craniofacial spatial data consists of the two-dimensional and three-dimensional images of facial soft tissue, hard tissue (skull) and all related measurements, i.e. anthropometric and cephalometric measurements, respectively. In conventional practice (i.e. at the School of Dental Study, University Sains Malaysia, Kubang Kerian, Kelantan), the three-dimensional model of facial soft tissue data is obtained by using the physical contact method, where by the safety plaster was used to produce a physical three-dimensional model of the craniofacial. In terms of the anthropometric measurements (either linear or curve measurements), the calipers were used where the surgeon need to touch the craniofacial surface. In general, the problems involved in this study are:

a. The lack of high accuracy data acquisition system to capture 3D craniofacial spatial data in Malaysia. In modern computer vision technology, the process of acquiring three-dimensional model of craniofacial is based on the non-contact technology such as close-range photogrammetry and laser scanning.
b. The lack of suitable, practical, safe and high accuracy method for the measurement of craniofacial landmarks (anthropometry). Conventional anthropometry method, which was based on contact method exposed to errors in the measurements. In modern computer environment, the measurement of craniofacial landmarks can be done automatically using the computer software. Although photogrammetry and laser scanning are useful tools for the landmark measurements, there are no reliable standards and designated measurement techniques for craniofacial application.
c. The lack of complete 3D craniofacial spatial data. Most of the 3D craniofacial spatial datasets was not complete in-term of the coverage of the data. For example, the 3D laser scanner datasets did not include both ears where the ear measurements (width, length, insertion, location, inclination and protrusion) could not be done. The most critical issue is the dataset could not be used in craniofacial study, since the acquired craniofacial landmarks needed for the determination of the Frankfurt plane was located at the ear. Although laser scanning system was supposed to be the higher in accuracy and faster in data collection, there is still a limitation which generated

incompleteness of the data due to the in-correct scanning angles and dark facial features such as eye brows, beard and eye balls. For a complete development of 3D craniofacial spatial surface, the integration of craniofacial datasets is highly needed to improve the geometry, accuracy and visual quality of the datasets.

1.3 Objectives

The main objectives of this study are:

a. To develop a prototype Craniofacial Spatial Data Acquisition System based on the integration of stereophotogrammetry and 3D laser scanning techniques.

b. To develop a 3D calibration method for high accuracy calibration of a Prototype Craniofacial Spatial Data Acquisition System.

1.4 Scope of Study

The scope of this study involved the application of stereophotogrammetry and laser scanning systems for medical purposes and it focused on the study of human faces (i.e. craniofacial area).

a. The stereophotogrammetric method will be used to capture high resolution stereo images of the craniofacial, while the laser scanning method will be used to capture fast and accurate three-dimensional surface model of the similar craniofacial area. Consequently, a set of four stereo images and two laser scans data will be used for each subject/patient.

b. The calibration of stereophotogrammetry and laser scanning sensors will be carried out separately and will involve the study of the reliability, accuracy, outlier detection and error propagation of each sensor.
c. The study will involve the integration of stereophotogrammetry and laser scanning systems for the improvement of geometry, accuracy and visual quality of the craniofacial spatial data.
d. The performance of developed data acquisition system and the integration results will be evaluated using craniofacial anthropometric approach.

1.5 A Brief Note on the Methodology

Figure 1.1 shows the methodology involved in the study. The methodology involved three main components, (a) development of Craniofacial Imaging System, (b) development of System Calibration and (c) integration of photogrammetry/laser scanning system. Each component consisted of related activities.

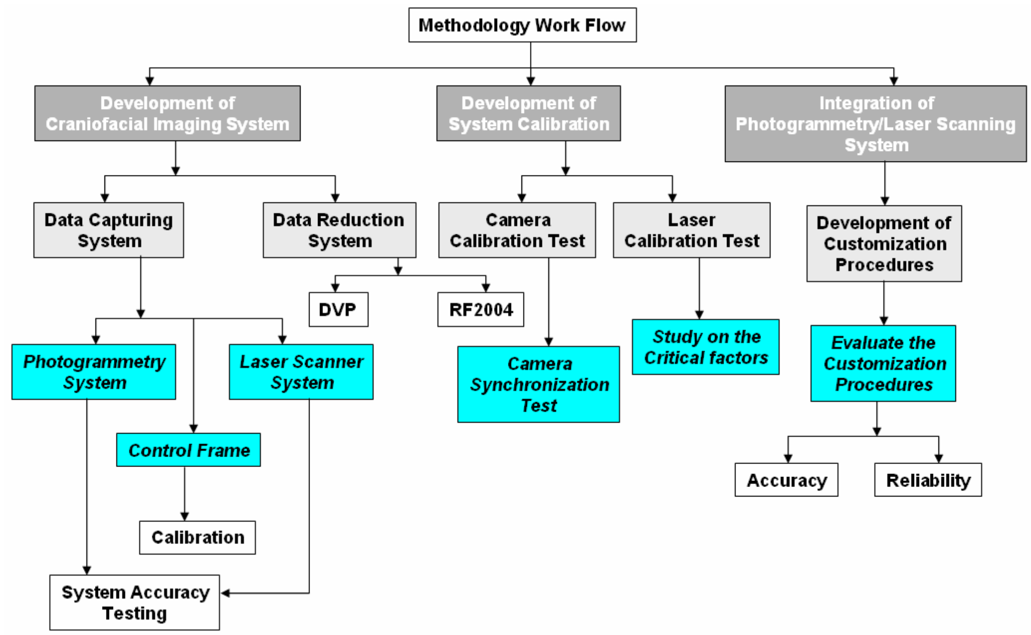


Figure 1.1: Methodology workflow

a. Development of Craniofacial Imaging System

The activities involved in the development of Craniofacial Imaging System are the development of data capturing system and data reduction system. The data capturing system involved the development of craniofacial photogrammetry system and introducing the laser scanning system. Both systems involved the accuracy testing on craniofacial landmark measurement. It also involved the development of craniofacial photogrammetric control frame, which is used to provide high accuracy control for the stereo orientation process.

b. Development of System Calibration

The development of system calibration involved calibration of the cameras and laser scanners. It also involved the study on the camera synchronization and laser scanner critical factors for the use of craniofacial mapping.

c. Integration of Photogrammetry/Laser Scanning System

The integration of photogrammetry/laser scanning system involved the customization of an existing integration procedures. The customization procedures were evaluated under the accuracy and reliability aspects.

1.6 Expected Outcomes

At the end of the study it is envisaged that prototype craniofacial spatial data acquisition system is available for the craniofacial surgeons to obtain high resolution stereo images and high accuracy 3D surface model of the craniofacial features. The outcomes also involve the following:

a. A set of procedure for acquiring high accuracy stereo image of the craniofacial features.
b. A set of procedure for acquiring high accuracy 3D craniofacial spatial data using laser scanners.
c. A set of procedures to evaluate the synchronization of multi-camera in craniofacial data capture.
d. A set of procedures to obtain all anthropometric measurement of craniofacial landmarks using stereophotogrammetric system.
e. A set of procedures to obtain high accuracy 3D craniofacial surface model based on the integration of photogrammetry and 3D laser scanning datasets.

1.7 Contributions of the Study

The contributions of the study are:

a. Development of a new multi-sensor technique for capturing high accuracy 3D craniofacial soft tissue data for the purpose of craniofacial reconstruction surgery in Malaysia. Two sensors namely stereo cameras and laser scanners were used to capture the complete craniofacial features. The stereo cameras were used to capture high resolution stereo images, while 3D laser scanner was used to capture 3D surface model.
b. Development of techniques and devices to improve the photogrammetric measurement accuracy. Stereocameras comprise of eight high resolution professional digital cameras, which were synchronized using external shutter devices to reduce and eliminate error due to movement of craniofacial features.
c. Development of methods to calibrate the 3D imaging sensors developed in (a). The stereo cameras and the laser scanners were calibrated separately using appropriate 3D calibration approach.
d. Development of a non-contact method for craniofacial landmarks identifications and measurements based on the integration of stereophotogrammetry and 3D laser scanning techniques.
e. Development of a practical approach for high accuracy 3D modelling of craniofacial soft tissue data by the integration of stereophotogrammetry and laser scanning 3D dataset. The integration involved the 3D point clouds registration using high accuracy photogrammetric targets.

1.8 Research Contents

This research consists of seven chapters. Table 1.1 described the summary of each chapter.

Table 1.1: Summary of research chapters

Chapters	Summary
1	Describes the introduction of the research background, problem statements, objectives, and scopes, brief on the methodology, expected outcomes, contributions of the study and research contents.
2	Describes the state-of-the-art of craniofacial imaging system through comprehensive review of related works that has been carried out by world wide researchers.
3	Describes the method implemented in the development of a prototype Craniofacial Imaging system.
4	Describes the method implemented in the system calibration.
5	Describes the method implemented in the integration of photogrammetry and 3D laser scanning system for the improvement of craniofacial point clouds registration accuracy
6	Describes the results and analysis
7	Describes the discussion, suggestion for further research and conclusion

CHAPTER 2

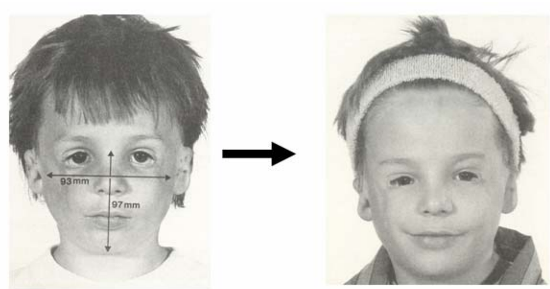
STATE OF THE ART OF CRANIOFACIAL IMAGING SYSTEM

2.1 Introduction

Essentially, the craniofacial spatial database must be able to handle many forms of raster format spatial data such as CCD camera images, CT scanner images and scanned cephalometric radiographs. In addition, many forms of vector spatial data are essential, which may include data obtained from photogrammetric systems, laser 3D scanning systems or conventional anthropometric measurement techniques. Attribute data are also needed in the craniofacial database. Examples are patient medical detail, pre-surgical intervention and post-surgical intervention data.

For the pre-intervention planning of the craniofacial corrective and reconstruction surgery, several forms of 3D spatial data must be available. These craniofacial feature and shape information include craniofacial digital 3D surface spatial data, 3D soft tissue spatial data, 3D anthropometric measurement, 3D CT scan spatial data, 3D hard tissue spatial data and occasionally, digital 2D cephalometric radiographs. Secondary 3D spatial data such as patient’s parents’ or sibling’s craniofacial features may also be required for planning purposes. These data are essential for planning of a particular type of craniofacial surgery in which accurate pre-surgical data is not available. For example, an accident or burnt patient may not have accurate pre-intervention data for reconstructive surgery. Monitoring of post-surgical intervention also requires accurate pre-surgical intervention craniofacial spatial data.

Spatial craniofacial data of the ‘normal range’ group (Farkas 1994: 73) of the population are needed to plan craniofacial reconstruction of malformation patients because the normal data are often used as the correct dimension for surgery (Cutting *et al*. 1998; Madjarova *et al*. 1999) (Figure 2.1). Kolar and Salter (1997; p232) stated that the absence of adequate comparative data for non-European populations is increasingly becoming a problem for analysing patterns of dysmorphology or planning surgical corrections. In addition, the normal data are required for forensic applications, namely: a) identifying a body (skeletal remains), b) predicting the current profile of the individual and c) estimating the age of the individual (Giles and Elliot 1963).



Measurement	Landmarks	Actual	Normal	Proposed	2 years postop
Face width	zy-zy	93mm	102-125mm	113mm	108mm
Face height	n-gn	97mm	82-105mm	No change	99mm
Facial Index	n-gn/zy-zy	104.3	71.8-92.2	85.8	91.7
Biocular width	ex-ex	69mm	72-86mm	-	71mm

Figure 2.1: The use of normal craniofacial anthropometry data for planning and correcting the malformation patients (Kolar and Salter, 1997)

Malaysia is a multi-racial country, whereby non-Europeans (Malays, Chinese and Indians) form the bulk of the population. However, the cost of setting up a craniofacial national database is expensive, in particular the craniofacial data capture. Therefore, it is essential that proper planning and investigation be carried out before commencing the data capture phase. This chapter provides an evaluation of the current craniofacial spatial data capture techniques and systems. The evaluation will help the author to develop a multi-technique photogrammetric/laser 3D scanning technologies.

2.2 Spatial Data Requirement

According to Farkas (1994) a basic craniofacial spatial database should contain a set of anthropometric linear and angular measurements, which could be used to define the shape and size of a human craniofacial. Examples of the linear measurement were the width of the forehead and the circumference of the head respectively. The angular measurements could be inclination or angles. Examples were the inclination of the anterior surface of the forehead and the mentocervical angle, which was formed by the upper contour of the chin and the surface beneath the mandible respectively. A complete craniofacial examination required 135 linear and 59 angular measurements (Farkas 1994). Nevertheless, the basic set of anthropometric measurement was no longer adequate for the modern multi-purpose national database, which would be required for quality corrective and reconstructive surgeries, forensic investigation and scientific research.

According to Kolar and Salter (1997), accurate measurement of craniofacial landmarks required precise identification of landmarks. The total of 45 landmarks is needed to be identified and measured (Figure 2.2). The location of the landmarks can be classified in six categories, head, face, orbits, nose, orolabial and ears. Table 2.1 to Table 2.6 shows the information regarding craniofacial landmarks.

Figure 2.2: A front, lateral, superior and submental vertex view of head and face showing craniofacial landmarks (Kolar and Salter, 1997)

Table 2.1: Craniofacial landmarks-location on the head

Landmarks	Level used	Definition
Euryon	eu	The most lateral point on the head
Frontotemporale	ft	The most medial point on the temporal crest of the frontal bone
Frontozygomaticus	fz	The most lateral point on the Frontozygomatic
Glabella	g	The most prominent point in the median sigittal plane between the supraorbital ridges
Ophyron	on	The point, at the mid plane, of a line tangent to the upper limits of the eyebrows
Opisthocranion	op	The most prominent posterior point of the occiput
Porion	po	The most superior point on the upper margin of the external auditory meatus when the head is in the Frankfurt horizontal plane
Tragion	t	Located at the notch above the targus of the ear
Trichion	tr	Midpoint of the hairline
Vertex	v	The highest point of the head
Condylion laterale	cdl	

Table 2.2: Craniofacial landmarks-location on the face

Landmarks	Level Used	Definition
Condylion laterale	cdl	The most lateral point on the mandibular condyle
Gnathion	gn	The lowest point in the midline on the lower border of the chin
Gonion	go	The most lateral point at the angle of the mandible
Nasion	n	The midpoint of the nasofrontal suture
Pogonion	pg	The most anterior point in the middle of the soft tissue chin
Subnasale	sn	The junction between the lower borders of the nasal septum
Stomion	sto	The midpoint of the labial fissure when the lips are closed naturally
Zygion	zy	The most lateral point of the zygomatic arc

Table 2.3: Craniofacial landmarks-location on the orbits

Landmarks	**Level Used**	**Definition**
Endocanthion	en	The inner corner of the eye fissure where the eyelids meet
Exocanthion	ex	The outer corner of the eye fissure where the eyelids meet
Orbitale	or	The lowest point on the margin of the orbit
Orbitale superius	os	The highest point on the margin of the orbit
Palpebrale inferius	pi	The lowest point in the middle of the margin of the lower eyelid
Palpebrale superius	ps	The higest point in the middle margin of the upper eyelid
Superciliare	sci	The highest point on the upper margin of the middle portion of the eyebrow

Table 2.4: Craniofacial landmarks-location on the nose

Landmarks	**Level Used**	**Definition**
Alar curvature point	ac	The most posterolateral point of the curvature of the base of the nasal alae
Alare	al	The most lateral point on the nasal ara
Columella apex	c’	The most anterior point on the columella crest
Maxillofrontale	mf	The anterior lacrimal crest of the maxilla at the frontomaxillary suture
Nasal midline	m’	The midline of the bridge of the nose
Pronasale	prn	The most protruded point of the nasal tip
Sellion	s	The deepest point of the nasofrontal angle
Subalare	sbal	The point of the lower margin of the base of the nasal ala

Table 2.5: Craniofacial landmarks-location on the orolabial

Landmarks	Level Used	Definition
Cheilion	ch	The outer corner of the mouth where the outer edges of the upper and lower vermilions meet
Crista philtri	cph	The point of the crest of the philtrum
Labiale inferius	li	The midpoint of the vermilion border of the lower lip
Labiale superius lateralis	ls’	The point on the upper vermilion border directly inferior to subarale
Labiale superios	ls	The midpoint of the vermilion border of the upper lip

Table 2.6: Craniofacial landmarks-location on the ears

Landmarks	Level Used	Definition
Otobasion inferius	obi	The lowest point of attachment of the external ear to the head
Otobasion superius	obs	The highest point of attachment of the external ear to the head
Postaurale	pa	The most posterior point on the free margin of the ear
Preaurale	pra	A point on the ear insertion line opposite postaurale
Superraurale	sa	The highest point of the free margin of the ear
Subaurale	sba	The lowest point of the earlobe

From 45 identified craniofacial landmarks, six types of measurements (consisted of 74 measurements) need to be performed. The six types of measurements are cranial measurements, facial measurements, orbital measurements, nasal measurements, orolabial measurements and ear measurements. The measurements were divided in linear measurements and angled with inclination measurements.

After discussion with a group of craniofacial surgeons from the Universiti Sains Malaysia (USM) it was clear that the craniofacial database should provide data for the following modern applications:

a. Evaluating the abnormality of a patient's craniofacial (e.g. asymmetric of the head, face and jaws);
b. Pre-surgical intervention planning and post-surgical evaluation of malformation craniofacials;
c. Pre-surgical and post-surgical evaluation of trauma patients;
d. Forensic identification of both the living (e.g. missing person) and the dead (e.g. skeletal remains) and
e. Digital 3D models for solid modelling.

To satisfy the requirements of the first application, stereo-photographs were needed to capture the anthropometric linear and angular measurements. In addition, the stereo-photographs should be available for updating and referencing in the future. The data requirement of the second, third and fourth were similar. To carry out these applications three-dimensional (3D) soft tissue model (skin surface) and hard tissue (i.e. skull, jaw and teeth) models were needed. Photogrammetry, laser 3D scanning technique, structured light modelling and many other developed techniques could obtain the soft tissue model. CT scan and cephalometric radiograph and Magnetic Resonance (MR) image could provide the hard tissue model. In the fifth application, a 3D solid model of the skin surface and the hard tissue would be needed for patient consultation and classroom illustration purposes. These solid models could be created using Rapid ProtoTyping technology (RPT).

2.3 Spatial Data Accuracy

This was one of the most important factors in the development of the photogrammetric/laser 3D scanning system because it could affect the accuracy of the craniofacial spatial database. To review the accuracy of the existing databases one needs to go no further than the set of data provided by Kolar and Salter (1997). In the data, a set of manually obtained anthropometric linear and angular measurements was available. The authors provided the population standard deviation of all the important anthropometric measurement of a group of 18 years old females. The smallest recorded standard deviation of these anthropometric measurements was 0·7mm. That is, the population showed a deviation of 0·7mm for the distance connecting two particular anthropometric marks. In other words, a 0·7mm difference or one standard deviation of the population means in the anthropometric distance between two individuals was not noticeable visually (Farkas 1994:p73; Evereklioglu et al 2002). However, Kolar and Salter (1997) also argued that a 1mm inferior dislocation of both endocanthion (en) and exocanthion (ex) could produce an obvious deformity even though the measurements of the eye fissures, length, width and inclination were otherwise symmetrical. Thus, the accuracy in locating some craniofacial landmarks was more important than the others.

Gabel and Kakoschke (1996) reported a clinical requirement of all facial measurements to have an accuracy of 0·1 mm. However, the authors did not refer to any specific standards or specifications. Similarly, Ayoub et al. (1998) stated that a relative accuracy of 0·5 mm is required for work relating to three-dimensional spatial data capture for surgical planning purposes. Again, the specific standards or specifications were not stated. It was difficult to identify the majority of the anthropometric marks for subsequent measurement to such high precision except where a signalised target was placed over the position permanently. Obviously, there are two sets of identifiable accuracy:

a. *Digitising accuracy*, which depends on the system and the signalised target used, and
b. *Landmarks location accuracy*, which depends on the anthropologist or the clinician who place the signalised target.

On the whole, any substantial improvement in the accuracy also increases the cost of capturing the data. Moreover, the skill of personnel required to capture the data from images can also increase substantially. The demand for skilled personnel in rural hospitals may put a strain on the budget of setting up a national database.

After consultation with a group of craniofacial surgeons it was clear that the existing accuracy of the manually obtained anthropometric measurement was adequate. Consequently, for the first application, a value of 0·7mm (Kolar and Salter 1997) for the overall anthropometric linear measurement accuracy was adopted. Therefore, the stereophotographs should provide an accuracy of ± 0·7mm at one standard deviation for all the measured vectors. For the second and third applications a ± 2·0mm was agreed. This value was determined by the contour tracing method, which is significantly less accurate than the spot elevation method (Wolf and Dewitt 2000). In conjunction with photogrammetry, we used a laser-based structured light triangulation technique (laser 3D scanning) was used to obtain 3D surface data, recognizing the disadvantage of possible patient movement between the stereophotography and the scanning. In view of the large number of patients required for the first phase of the project, the efficiency of such technology as laser 3D scanning outweighed the drawback.

2.4 Method of Craniofacial Spatial Data Capture

In view of the accuracy requirement of the spatial data and the amount of data needed to populate the craniofacial database, it was essential to review the techniques for spatial data capture, particularly, an efficient 3D surface remote measuring technique. Hu and Stockman (1989) listed four basic common remote measuring techniques, which are still relevant today, as follows:

a. **Stereo disparity**: The method simulates the two eyes of a human. Depth can be measured in manual mode or automated mode. This technique is commonly known as photogrammetry.
b. **Structured light**: An artificial-light source such as Laser is used to illuminate a surface with a pattern. A photograph of the patterned surface is used to compute the depth using the triangulation algorithms. A common precise method in this category is known as laser 3D scanning.
c. **Direct ranging or profiling**: An example is laser range finder, which measures depth by timing the laser travel.
d. **Shape-from techniques**: These monocular approaches recover the relative depth from texture, from shading, from contours or from motion; resulting in the surface orientations with respect to a viewer-centred coordinates system.

Many commercial systems have been developed based on these or variants of these techniques. However, it was decided to develop a system, which is based on the technology which was familiar and which would be adequate for the research. Consequently, only photogrammetry and laser 3D scanning were selected for the study. A brief discussion of the selected techniques and the conventional anthropometric measurement technique are provided below.

2.4.1 Conventional Measurement Technique

No amount of argument in favour of the newly introduced method could be considered complete without a proper discussion of the existing technique. Traditionally, craniofacial data were obtained using standard anthropometric instrument such as callipers, measuring tapes, compasses, protractors and angle finders (Kolar and Salter 1997) (Figure 2.3). Farkas (1994) stated that the anthropometric examiner should be familiar with the:

a. areas in which the tip of the instrument used must be pressed to the bony surface to obtain correct measurement and
b. areas where the instrument barely touches the skin surface at measurement. Farkas (1994) argued that accurate measurement required correct use of the standard anthropometric instruments and knowledge of the peculiarities of the landmarks.

Standard tools for curve surface measurement could produce large errors because the line and angle of measurement were subjected to the interpretation of the anthropometric examiner. In addition, both the examiner and the patient were often faced with uncomfortable and lengthy measurement sessions. The conclusion was that only a small number of measurements, which still requires standard anthropometric instrument. These measurements would include all the cranial landmarks above the hairline, the circumference of the head and missing regions present in photogrammetry. The cause of the missing regions in photogrammetry and laser 3D scanning technique was due mainly to occlusions and obstruction by hair.

Figure 2.3: Conventional measurement techniques using calliper (Kolar and Salter, 1997)

2.4.2 Stereo Disparity: Photogrammetry

Single, stereo or multiple image close range photogrammetry have been used for the recording and mapping of human body parts since the turn of the last century (Mitchell and Leemann 1996). Generally, the medical and dental professionals favoured the simple single image measurement techniques. They used the images to determine the length of feature, the angle between features or relative depth of features (Akimoto et al. 1993; Brusati et al. 1996; Berger et al. 1999; Fanibunda and Thomas 1999; Nechala et al. 1999). Nevertheless, 3D model generation, contour plots of the craniofacial and 3D anthropometric measurements have been researched extensively (Domokos and Kismartoni 1974; Newton 1974; Wright et al 1974; Deacon et al 1991; Banda et al. 1992; Ferrario et al. 1996; Ferrario et al. 1995; D’Apuzzo 1998; Ferrario et al. 1999; Frey et al. 1999; D’Apuzzo 2002).

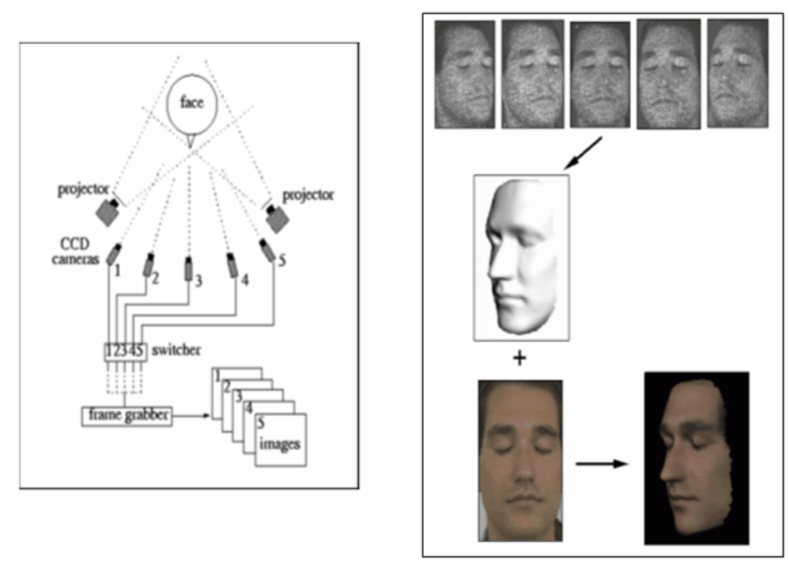


Figure 2.4: Multiple image close-range photogrammetric technique for capturing of human faces (*D'Apuzzo, 2002*)

Images for close range photogrammetry can be acquired using film-based cameras, analogue video cameras or digital still-frame cameras/video cameras. Films must be scanned into digital form using scanners; analogue video must be frame-grabbed into digital form while digital systems output images in digital form directly (Schenk 1999). By and large, a digital system is the most advantageous because film scanning and frame-grabbing requires additional resources.

Figure 2.5: Camera used in close-range photogrammetry

Basic camera calibration is essential for all photogrammetric camera involving accurate measurements of its photographic images. Camera calibration software has become more user-friendly for non-metric film-based cameras and digital cameras in recent years (Dowman and Scott, 1980; Fryer 1989; Beyer 1992;

Peterson et al. 1993; Shortis et al. 1996; Fraser and Edmundson 1996). The process includes the determination of the CCD format size, principal point of autocollimation, the principal distance, and the radial lens distortion parameters.

Photogrammetric control for stereophotography of the craniofacial mapping is well documented. In Savara and George (1984) a typical frame was placed over the patient's head; in Peterson et al. (1993) a frame was placed near both sides of the head and in Schewe and Ifert (2000) control targets were placed on a helmet. These three designs almost certainly covered all published photogrammetric control configuration. Frequently, these controls were attached to cephalostat for study involving the lower craniofacial feature.

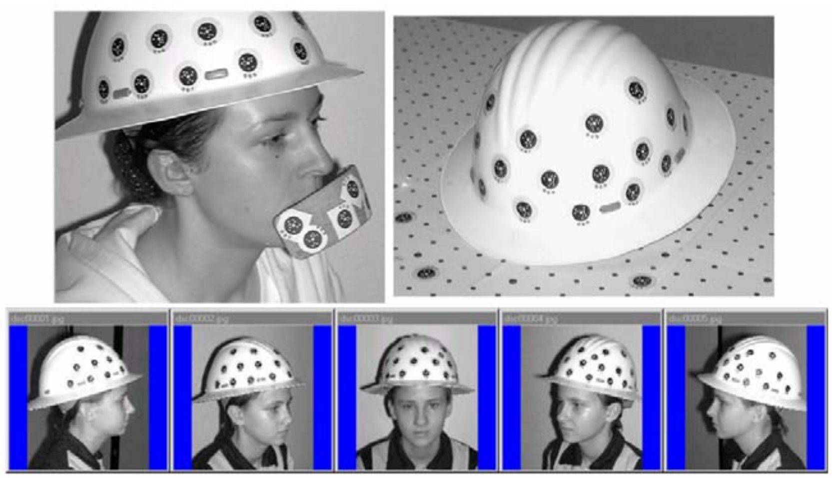


Figure 2.6: Photogrammetric control- control targets were placed on a helmet (*Schewe and Ifert, 2000*).

For the stereo-photogrammetry technique, Ferrario et al. (1999) applied 2-mm reflective markers and Cacou et al. (1997) applied 5-mm diameter blue vellum paper on the landmarks. Ferrario et al. (1999) reported an accuracy of 0.1mm using an automated digitising technique while an accuracy of 0·5 mm using a manual digitising technique was reported by Newton (1974).

Once a stereopair of photographs of the craniofacial was taken, interior, relative and absolute orientation could be carried out either manually or automatically using Soft-copy photogrammetric software (Schenk 1999). Also, point of interest on the stereo model could be captured manually or automatically (Wolf and Dewitt 2000; Schenk 1999). In the latter, a Digital Surface Model (DSM) of the stereomodel could be obtained instantly. However, there is a small amount of editing because the craniofacial has a complex shape. Editing could involve the removal of error and the addition of break line and ridge-line (Schenk 1999). Nonetheless, the 3D point cloud created through stereo-photogrammetry consists of a set of points with each point having a set of 3D coordinates. The spatial accuracy of the technique depends mainly on the geometry of the images used, the resolution of the CCD camera and the image processing technique. Generally, the desired mapping accuracy can be controlled simply by altering the focal length of the lens, the object distance and the pixel resolution of the CCD of the camera. Relative object-space accuracy of 0.5 mm or higher can be achieved using stereo or multiple photographs routinely (Newton 1974; Burke et al. 1983; Hay et al. 1985; Deacon et al. 1991).

2.4.2.1 A Brief Discussion on the Application of Stereophotogrammetric System for Capturing of Craniofacial Spatial Data.

From the review we can see that close-range photogrammetric technique was widely used in capturing of craniofacial spatial data. We can divide the technique into two categories: (a) 3D stereo-photogrammetry, and (b) 3D convergent photogrammetry. The aim of both techniques is to develop a 3D model of human face from 2D images captured using calibrated cameras. The 3D stereo-photogrammetry which involved the photogrammetric triangulation method directly generates the three-dimensional craniofacial model from two or more stereo cameras. The output of this system is a computerized three-dimensional craniofacial surface model. The anthropometric landmarks were than digitized on the surface and the measurements (distances and angles between landmarks) were done automatically.

The 3D convergent photogrammetry involved the used of multi cameras and projectors as main components to capture multi-image. The image matching technique was applied to measure the 3D coordinates of the projected pattern on the facial surface. The 3D coordinates were than used to constructed 3D surface model using developed computer software. Extra images need to be captured either using digital camera or video camera for texture mapping.

In this study, the optical stereo-photogrammetry technique will be used to capture stereo images of craniofacial features and to form the identification and measurement of the craniofacial anthropometric landmarks. The technique does not involve the development of 3D surface model of craniofacial features. The technique was based on the basic stereo-photogrammetric mapping that has been applied in topographic mapping using aerial photographs. The accuracy of the technique depends on several factors such as high resolution digital images, camera calibration, camera synchronization, stereo overlap, stereo base distance, stereophotogrammetric orientation and sterephotogrammetric digitizing. In general, the stereo images are processed using stereo orientation software such as DVP via stereo photogrammetric workstation environment.

The method is practical to use because each craniofacial landmarks was measured in 3D environment, via stereoscopic devices, which is similar to the measurements of the craniofacial landmarks using calipers. Even method (b) promised to be the most the accurate solution for photogrammetric measurement but it is not practical and not suitable for the craniofacial landmarks identification and measurement, since the aim of the study is to apply a fully non-contact method. The implementation of method (b) in measuring craniofacial landmarks required markers marked on the craniofacial features. This is because the digitization of landmarks was done on 2D images. The three-dimensional craniofacial surface, which is developed by method (a) and (b), was also found to be time consuming since more time is involved in 3D reconstruction to develop 3D model and the measurements can only be done after getting the 3D model. The resolution of the 3D surface model generated by the method depends on the resolution of the camera used to capture the images. To avoid the above problem, the laser scanning technique is used in the study to capture the 3D surface model of craniofacial features. This technique has been used widely to capture high accuracy 3D surface model within one second data capturing period. The precision in depth make the laser scanner become the very high accuracy method to capture complex 3D surface such as craniofacial surface.

2.4.3 Structured Light: Triangulation

This technique is often known as 3D laser scanning in the medical journals and the same name is applied to this study. The surface of the object is illuminated with an artificial light, which may be any structured light or any shade of pattern. Assuming that the light is projected in a single plane, a triangulation algorithm can determine the depth of the surface. Details of the mathematics can be obtained in Boyer and Kak (1987), Sanderson et al. (1988) and Hu and Stockman (1989). Generally, the system consists of a structured laser light source, a light projection system and a digital imaging system. The structured laser beam creates an ultra-thin profile on the object, which is photographed by a CCD camera mounted close to the projector. The relative position (a vector) between the international reference point of the projection system and the camera lens is fixed. In addition, the angle of each projected laser profile plane and the angle of the camera optical axis are calibrated in advance. Subsequently, the x, y and z coordinates of the object-space position of each pixel on the object can be computed using the scale of the photography, the relative positional vector and the known angles. A least squares technique is used to compute a set of optimum 3D coordinates of the object surface. The texture and radiometric value of the CCD images may be added to the 3D data to obtain a realistic surface model of the object. Additional information of the system for medical application can be found in Bush and Antonyshyn (1996), Cacou et al. (1997), Yamada et al. (1998), O’Grady and Antonyshyn (1999) and Bernardini et al (2001).

The spatial accuracy of a triangulation system is dependent on the focal length of the camera, the object distance, pixel size of the CCD camera, the number of cameras used and the mathematics, which determines the centre of the projected light beam. Kuroda et al. (1996) reported a measurement error of 0·05 mm using dual high precision CCD cameras 3D-VMS250R produced by UNISN, Inc., Osaka Japan; Bush and Antonyshyn (1996) gave a spatial resolution of 0·5 to 2 mm in the x, 0·6 mm in the y and 0·1 to 0·4 mm in the z (depth) for a single-camera Cyberware 3030RBG digitiser. Minolta gives a depth precision ranging from 0·04 to 0·09 mm for the VI 910 system.

For the 3D laser scanning technique, Bush and Antonyshyn (1996) used 2-mm diameter fluorescent markers. The authors reported an accuracy of 0·6-mm for signalised landmarks and an accuracy of 1-mm for non-signalised landmarks of laser 3D scanned model.

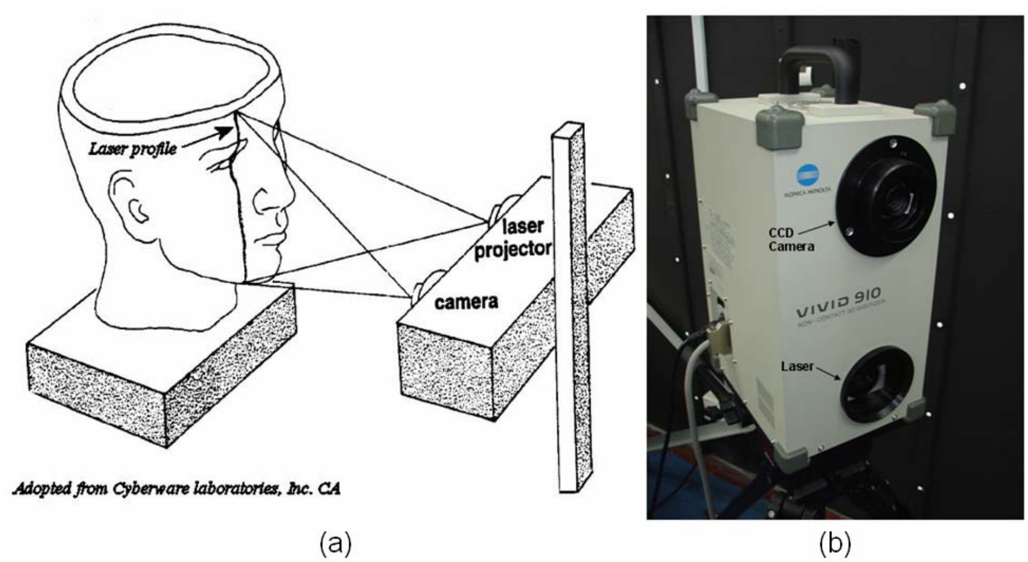


Figure 2.7: (a) Structured light triangulation technique. A laser beam is projected onto the surface and the adjacent camera records the position of the beam. During a scan many hundred of profiles are recorded along the surface; (b) A Minolta VI 910 laser scanner.

Generally, an off-the-shelf system is fully supported by a suite of software, which includes system calibration, data capture and data editing. To start a scanning session it is necessary to calibrate the system with a supplied calibration chart, which is placed on a rotary stage controller in front of the camera. A view of the scanned area is displayed on the system viewfinder. The data capture phase is fully automated. The speed of point capture may range from 15 000 points to 230 000 points per second. After a scan the 3D point cloud may be displayed and edited on the computer screen using third party software such as RapidForm (INUS Technology Inc.).

2.4.3.1 A Brief Discussion on the Application of 3D Laser Scanning System for Capturing Craniofacial Spatial Data.

From the review it can be seen that laser scanning technique has been widely used in modeling and measuring craniofacial spatial data for the purposed of craniofacial, maxillofacial and orthodontic surgery. There are many types of laser scanners used and it can be classified as hand-held laser scanner, rotatable scanner and tripod set laser scanner. The tripod set laser scanners need more than one scanner to capture the human face because the coverage of each scans in the scanner is very limited. The used of one laser scanner in this situation required the shifting of the patient or the scanner to complete the scanning task that covered all surface on the object. The shifting effect can cause some errors in the alignment of the left scanned data and right scanned data. Laser scanner data need pre-processing process which includes 3D image registration. High accuracy is needed in this process in order to avoid errors in the measurement of craniofacial landmarks on the 3D surface. The measurements between landmarks that located on the same scanned surface will not effected by this error. However, most of the measurements need the combination between two scanned images.

In this study, the used of laser scanning system is to capture 3D surface model of craniofacial features. Two units of Minolta VIVID 910 laser scanners was used to provide optimum scanning coverage which covered from left ear to right ear and from hair line to bottom of the chin. The patient was asked to be seated with the head placed at the middle of the photogrammetric control frame. The stability of the head during scanning is controlled by using an adjustable head rest. The patient will be asked to open their eyes during scanning process. It is very important to get the 3D craniofacial surface model with both eyes opened because the appearance of two of the landmarks near the eyes (*en* and *ex*) was considered as important landmarks for craniofacial spatial data. Compared to the laser scanner used by the researchers (stated in the literature), the VIVID 910 laser scanner provided a scanning of 308,000 point clouds of craniofacial area (one scan) with fast scanning period and high accuracy 3D models. Both scanners were controlled using Polygon Editing Tool (PET) software and the 3D craniofacial surface was automatically displayed on the monitor screen.

From the review it is found that the scanning process need to be done more that one time per patient. At least two or three repeated scans are needed after finished the first scan task. The process will take time but will be benefit in the analysis part. The reason for having more that one scans at one session is to avoid the errors due to the movement of the face. In this study, the real-time accuracy analysis called “real-time shell deviation analysis” will be developed by customizing the RapidForm 2004 3D modeling software. In this analysis, the two scan data (shells) will be automatically registered and deviation between the scans will be analyzed automatically. The results which are the average standard deviation of the deviation will guide the operator either to continue for the next scanning process or not to proceed. This is a very important factor to be considered since we cannot get the similar craniofacial appearance when the patients are calling back for the data collection due to in-accurate 3D models.

This study also involved the comprehensive research on the laser intensity effect on the shape of the scanning object. To date, no researchers have discussed the optimum laser intensity used to gain the 3D surface model of human faces using laser scanning system. Laser intensity is a very important factor in the used of laser scanning technology especially when scanning craniofacial soft tissue (skin). The laser intensity can affect the shape of the 3D model and can create errors in the model. Laser intensity involved with the width of laser light that transmit from the scanner onto the object. It's normally presented as the size of laser diode (LD). The bigger the value set for LD, the bigger the width of transmitted laser light. More LD value means more laser power.

2.4.4 Advantages and Drawbacks

The major advantages of photogrammetry are: it is non-invasive, instantaneous, high accuracy, real-world colour and texture and it provides a permanent record. A permanent record allows re-measurement if it is needed. The major drawbacks are: there is lack of soft (skin and flesh) and hard (bone) tissue registration and there are always occlusions or obstructions on the images. The major advantage of laser 3D scanning is its speed of point capture and it ultra-high accuracy. There are four drawbacks for craniofacial application which are:

a. Accuracy can degrade substantially if the patient moves during the process of scanning or in between scans,
b. A dark skin colour can affect the intensity of reflected light,
c. Creating break-line for ridges and valleys is both tedious and slow and
d. There is no permanent record like the photogrammetry technique.

The integration of 3D laser scanning with photogrammetry was seen to be the optimum solution to overcome the above drawbacks.

2.5 Integration of Close-Range Photogrammetry and 3D Laser Scanning Systems – An Overview

2.5.1 Introduction

Close-range photogrammetry and 3D laser scanning technology are widely used to automatically, accurately, reliably and completely measure, in three dimensions, objects, sites or scenes. Integration or fusion of multi imaging systems (such as Close-range photogrammetry and 3D laser scanning technology) for mapping documentation has become a popular issue in the last two years. Even the imaging system was claimed to be the better in accuracy, modeling and measurement, there still a limitation which cannot be successfully provided. The aim of the integration is to improve the accuracy of the final mapping results. The issue of the integration of photogrammetry (either close-range photogrammetry or aerial photogrammetry) and laser scanning has been applied into many applications. The integration became more reliable since both methods can deliver similar type of products the end users are accustomed to have, such as line drawing, digital terrain model (DTM), 3D surfaces and etc. Below is the detailed discussion on some of the integration applications.

2.5.2 Related Studies

Ionnidis and Tsakiri (2003) applied the integration of laser scanning and close-range photogrammetry for the creation of an accurate 3D solid model of a complex large statue. The need for the integration is higher in this application because close-range photogrammetry and metric surveying techniques has presented certain disadvantages for mapping smaller objects and much more complex objects such as statues. Laser scanning technology with the strange of automated data capture capabilities can satisfy most requirements of mapping a large statue. The combination and integration of photogrammetry and laser scanning is a suitable approach to improve the geometrical accuracy of the 3D model. In this study, non-contact 3D digitizer namely Minolta VVIVID 910 which was based on triangulation method was used to scan the large statue, while a complete close-range stereoscopic photographic documentation was successfully done using Hasselbland analog semi-metric cameras and Sony DSC-F7070 digital cameras. The cameras were calibrated using a 3D test fieldwith 130 targets with the accuracy of 2mm. Both methods were applied independently one after another. Close-range photogrammetry data collection involved with 22 stereopairs that covered the whole statue with precise control points while laser scanner was used to provide 649 20-30% overlapping scans data with 300,000 point clouds per scan. All the 22 stereopairs were orientated in SSK Z/I imaging digital photogrammetric workstation to generate the digital terrain model (DTM) and breaklines. The merging of all stereopairs was performed through characteristic tie points or natural points that lied in the overlapping area between the stereopairs. Laser scanning data processing involved the aligning and merging the scanned 3D models. Alignment process involved with the task to bring all the scans of the statue to a common coordinate system. For the high accuracy registration between the scan data, the triangle mesh registration method without target was used to merge the scanned data. Through the integration use of both imaging data, the geometry of any kind of object can be fully captured since the limitations of the objects that are self-covered are somehow narrowed with the availability of more data coverage. The integration process involved testing the compatibility of the two data sets by transferring dense horizontal sections derived from the merged data of the photogrammetric restitutions, onto the 3D solid model derived from the scans. By applying this stage, the systematic errors among the photogrammetric models was properly corrected. It also involved orthophoto production of parts of the statue using the TIN net derived from the scanned data and breaklines photogrammetrically produced.

Alshawabkeh and Haala (2004) integrate digital photogrammetry and laser scanning for heritage documentation. According to the authors, the integration helps to improve the geometry and visual quality of the collected 3D model of Al-Khasneh monument in Petra city, Jordan. In their study, the 3D point clouds were collected using 3D laser scanning system GS100 that was manufactured by Mensi. The system was being able to measure 5000 points per second. The Fuji S1 Pro digital camera was used to capture digital images of the façade. For the purpose of 3D modeling using laser scanner, five complete scans were produced and processed using Innovmetric software. The data was merged together and transform to absolute coordinate system. Although the 3D model produce by laser scanner is accurate, it is still difficult to recognize and localize the outlines of the surface features. Some of the data (cracks and edges outline) are lost and it is caused by the resolution of the laser data. Digital imagery was used to support the visual quality of such details. For the purposed of integration, both data sets have to co-registered which aligned the laser scanner data with the imagery. Since the corresponding points were difficult to detect in both data sets, three straight lines were measured between the image and laser data as corresponding elements to obtain a unique solution for spatial resection. The collinearity equations are applied to generate the distance image based on the available point clouds with the similar number of pixels of the corresponding images. The image segmentation was applied to automatically extract information on edges and linear surface features from the images then combined with laser scanner 3D data. By the integration process, the shape of 3D features can be determined accurately. The interpretation of point clouds and mesh models was improved using the available images.

According to *Beraldin (2004),* the multi-sensor data fusion techniques combine data from multiple sensors and related information is because of one aim, to achieve improved accuracies and more specific inferences than could be achieved by the use of a single sensor alone. The integration issues cover the situations where different sensors measure the same object / site from different locations or times or even users. The author focused the study on the propagation of errors for the generation of 3D model from multiple 3D acquisition methods. The errors will affect the overall metric accuracy of the final 3D model. Integration means alignment of 3D images from different sensors which was depends on the size of overlapping region between 3D images and curvature of the object surface. The propagation of errors occur when a 3D scanner can only produce the targeted spatial resolution and range uncertainty within a relatively small field of view compared to the overall size of object being surveyed. Thus, it is necessary to have a procedure by which the metric reliability of the 3D model can be assessed and guaranteed to an acceptable level by the combination of 3D scanner and photogrammetric solution.

Balis et al. (2004) develop a technique of integration of 3D laser scanning point cloud data and the video imagery produced by the Charge Couple Device (CCD) camera for the production of high accuracy and high resolution RGB textured models and orthophoto of archeological monuments. The main focus of the study is the computation of the relative geometry of the two imaging system, the camera calibration and their utilization in the fusion of the video data and the mesh model resulting from the scanner's point cloud. The geometric relationship between the two imaging system involved two intermediate reference systems which is the CCD camera reference system and the scanner reference system. The CCD camera reference system origin is the optical centre of the camera while the scanner reference system origin is the optical centre of the scanner measuring head. The work involved the use of Mensi laser scanning system to scan the archeological monuments in Ancient Ilida, Greece. The CCD camera video was used to capture the 2D RGB images (texture) of the monuments. The seven scanned data sets were registered and merged using Mensi RealWorks Survey Software. 2D texture was then registered on to 3D laser scan surface model by the implementation of the colinearity condition.

According to *Forkuo and King (2004)***,** the laser scanning technology could be seen as a complement to close-range photogrammetry. The integration or fusion of close-range photogrammetry and the new technology of terrestrial laser scanning methods, which have the ability to rapidly collect high resolution 3D surface information of an object, have offered new opportunities for photorealistic 3D model presentation, classification of real objects and virtual reality creation (fly through). The integration can be useful in texture mapping the point cloud to create photo realistic 3D models which are essential for variety of applications, extraction of reference targets for registration and calibration purposes, automation of 3D measurement and 3D reconstruction. The aim of the study was to develop integration of terrestrial laser scanner generated 3D data and 2D high resolution digital images for the creation of more complete and easy to interpret, than a model created from the 3D point cloud data alone. Three integration/fusion approaches were applied in the study, (a) integrates data from the two sensors (3D point cloud data and 2D intensity image), (b) feature detection and feature correspondence matching between the generated synthetic image and the intensity image acquired with digital cameras and (c) to relate each pixel in the 2D intensity image data to its corresponding sampled 3D point on the object surface. In the study, the Cyrax 2500 laser scanner was used to carry out the laser scanning to acquire a discrete representation of the object and a series of real color images (resolution of 3008 x 1960 pixels) were taken at different direction and position by a digital CCD camera. The author also introduced the mathematical model called a multi-sensor mathematical model, which is a physical model that describes the integration of 3D laser range camera and the CCD camera. In the study, the photogrammetric principles of collinearity condition with no systematic correction parameters was used as a basis for the implementation of the 3D transformation of 3D point cloud data to suitable 2D shape information. The 3D transformation involved the process of matching multi source data of the same object as well as to establish the correspondence between the sensors and to determine the geometric transformation that aligns one image with another. According to the author the image matching techniques comprises of two techniques, manual and automatic. The manual method was important in order to understand the key issues such as geometric quality and the resolution (both spatial and geometric) of the images. The automatic image matching method involved with correspondence matching where the extraction of features, generally interest points from both data sets. One of the methods is cross correlation matching method.

Demir et al. (2004) described the integration between terrestrial laser scanning systems with photogrammetric method for 3D modeling of building in Germany. According to the authors, the modern development of photogrammetric method and 3D laser scanning system for creating digital orthophoto, digital terrain models and monitoring process has become rapid, correct and economical. The ability of laser scanning system to generate thousands of 3D points over surface of interest in just a few minutes is an appealing concept. All the points were referenced to one internal coordinate system and a series of scans was necessary needed for the object with complex shape. In the study, the Cyrax laser scanner and the Pentax PAMS terrestrial metric stereo camera were used to acquire the spatial information of the object. The photogrammetric evaluation involved the use of stereo images for modeling the study area. A stereo photograph was taken at 18m object distance. The laser scanner coordinate system was used as a reference coordinate system. Laser scanning system was used to scan the study area. The object was controlled with the laser scanner's specific targets and the 3D modeling of the laser data was done using the Cyclone software. Through the combination of both sensors, the geometry of the study object is fully captured. The 3D orthophotos was successfully generated by orthoprojection of photos onto a unified dense DTM of the whole object derived from the laser scanner data. The integration results benefits to the architectural projects where the complete 3D model of the object was generated with real texture information.

According to *Bouroumand and Studnicka (2004)*, the integration of close-range photogrammetry and laser scanning technology was unique and highly efficient method to provide the true color textured 3D as-built models. The strength of the laser scanning lies in the fast and reliable rendering of surfaces, and the advantage of photogrammetry was the recognition of edges and details. Thus, the combination between the systems would be very benefitial in 3D modeling task. The study involved the 3D mapping of Bam Citadel historical area in Iran using the combination of RIEGL LMS Z420i laser scanner and calibrated Nikon D100 6 mega pixel digital camera mounted solidly on top of the scanner. The mathematical relationship between these two sensors was defined by perfect hardware calibration. The scanner and the mounted camera were operated one after another since the object remains fixed at the same location during data capture. The final result consists of a decimated data mesh with a high resolution texture using the Delaunary triangulation method. The mesh is to be cleaned and smoothed before the image data was applied in its entire pixel resolution. By matching the high resolution photographs on the scan data, it was possible to profit from both the high overall accuracy of the scanner as well as the detail identification capacity of photogrammetry and could easily generated orthophoto of the interest area far quickly away from the traditional methods.

2.5.3 Critical Discussion on the Integration of Close-Range Photogrammetry and Laser Scanning Systems

It is completely cleared that the integration between 3D imaging modalities will benefits the results of the work that applied 3D model as primary data sources. The three main benefits are:

a. *Improving the accuracy of the 3D surface model.*
b. *Improving the geometry of the 3D surface model.*
c. *Improving the visual quality (resolution) of the 3D surface model.*

The issues why the integration or combination or fusion between photogrammetry and laser scanning technology in modeling 3D surface is needed because of three factors, accuracy, geometry and visual quality. Many approaches have been applied in order to produce the integration between photogrammetry and laser scanning technology. From the literature review, the integration of both data sets was broadly applied for 3D modeling of monuments and archeological site but there is no such application involved in modeling the human faces. From the literature, there are few strategies/approaches for the integration between laser scanning and photogrammetric methods for the purpose of 3D modeling applications. The integration strategies are possible to apply in craniofacial modeling since both data sets provide the similar end products.

The possible strategies are:

a. High accuracy alignment of 3D laser scanner datasets using a correspondence 3D point that have been measured accurately using close-range photogrammetric method.
b. Photogrammetric facial orthophoto development using DTM or TIN generated from laser scanning data. The digital terrain model (DTM) can be generated by a few methods such as stereo photogrammetry and leveling survey. Both methods are time consuming. The strength of laser scanning method is fast and reliable for the generation of DTM. Thus, the period for orthophoto production will be shorter.
c. Measuring 3D anthropometric landmarks using stereophotogrammetric methods (stereo models) and registered the 3D landmarks on to 3D laser scanner surface model. Stereophotogrammetric method promised to be an accurate method for measuring the anthropometric landmarks since the measurements is in 3D environment with real texture visualization.
d. Development of 3D surface model of un-scanned craniofacial area using photogrammetry technique and registered the surface on to 3D laser scanning surface model. Although laser scanning technology promised to be a practical approach to generate the 3D surface model, there are still a limitations whereby dark features such as eye brow cannot be scanned successfully. Close-range photogrammetry with real texture images as a raw data can provide the solution.
e. Registration of 2D mosaic mapping of craniofacial surface on to 3D laser scanning surface model for high accuracy and high visual quality of real facial texture (photo realistic data). The job will involve 2D to 3D image transformation. The integration is purely valid because most of the laser scanning technology does not have very high radiometric resolution (support in built-in CCD camera), as in high resolution digital cameras used in modern close-range photogrammetric method.
f. The use of 3D coordinates of natural points derived from 3D laser scanning data as a control for stereo model absolute orientation process. The 3D laser surface with color texture will be used to digitize the edge of the natural

points. The lighting effect is a very important aspect to provide high quality of facial textures.

2.6 General Considerations for the Development of Craniofacial Spatial Data Capture

From the review the general considerations for the development of craniofacial 3D imaging system (Majid et al., 2005) was identified. The important considerations are:

a. Non-contact Anthropometric Measurement

The standard anthropometric technique requires physical contact by the anthropometric examiner throughout the measurement session. Physical contacts are not always desirable where religious or personal constraints forbid such contact. Conventional anthropometric measurement tools such as sliding calliper scan are very sharp. These tools can cause injury if a child becomes incooperative during a measurement session. In addition, many areas on the face are very sensitive to touch which may cause error in the measurement (Newton 1974). Furthermore, Wright et. al. (1974) argued that restraining an uncooperative patient often resulted in grimacing or distortion of the patient's facial features. In view of the fact that photogrammetry and 3D laser scanning are non-contact technologies, approved by the user requirement analysis; both techniques are considered vital for our data capture exercise.

b. Manual or Automated technique for anthropometric measurement

Various authors have discussed advantages and drawbacks of the automated anthropometric measurements. Automated anthropometric measurement involves pre-targeting anthropometric mark positions with signalised targets. These targets can be recognized by computer software (Gruen and Baltsaias 1989; Bush and Antonyshyn 1996; Cacou et al. 1997; Ferrario et al. 1996; D'Apuzzo 2002). Ferrario et al. (1996) reported an accuracy of 0.1 mm for all the 3D coordinates of 16 standardized facial landmarks automatically collected using a stereocamera system. Recently, Hattori et al. (2002) reported success with pre-coding target for automated recognition in Industrial Vision Metrology. Pre-coding target may be used to identify and digitise the landmark automatically. At this stage there is no plan to implement this technique in the project.

To satisfy the spatial data requirement, we need to examine each phase of the data capture. Firstly, we need anthropometric linear and angular data; secondly, we need a high quality stereo image for future updating, referencing and 3D surface rendering; and thirdly, we need an accurate 3D surface model of the craniofacial. To obtain anthropometric angular data requires human observation of a photogrammetric stereo model. The complexity of the arc and angle can only be appreciated by studying the specification given in Farkas (1994) and Kolar and Salter (1997). Consequently, an automated anthropometric landmark measurement technique satisfies our requirement only partially (about 70% of the measurements). However, one major benefit is that we can use pre-signalised targets to provide control points, which can help us to tie adjacent stereo models together. In addition these targets can be used to tie the laser 3D scan coordinates to the photogrammetric coordinate reference system. Consequently, the Ferrario et al. (1996) automation technique is applied for 16 standardized anthropometric landmarks, which are used as control points.

c. Design of Pre-signalised Targets

For the stereo-photogrammetry technique, Ferrario et al. (1999) applied 2-mm reflective markers and Cacou et al. (1997) applied 5-mm diameter blue vellum paper on the landmarks. Ferrario et al. (1999) reported an accuracy of 0.1mm using an automated digitising technique while an accuracy of 0·5 mm using a manual digitising technique was reported by Newton (1974). For the 3D laser scanning technique, Bush and Antonyshyn (1996) used 2-mm diameter fluorescent markers. The authors reported an accuracy of 0·6-mm for signalised landmarks and an accuracy of 1-mm for non-signalised landmarks of laser 3D scanned model. This study showed that the use of pre-signalised targets in the stereophotographs gave equally high accuracy measurement. Also tests showed that these targets provide high accuracy connection between adjacent stereo models. Subsequently, they provided high accuracy for the transformation of the laser 3D scan coordinates to the photogrammetric coordinate reference system. However, it is clear that the placing of the targets required an experienced anthropometric examiner.

d. Photogrammetric Control

Photogrammetric control for stereophotography of the craniofacial mapping is well documented. In Savara and George (1984) a typical frame was placed over the patient's head; in Peterson et al. (1993) a frame was placed near both sides of the head and in Schewe and Ifert (2000) control targets were placed on a helmet. These three designs almost certainly covered all published photogrammetric control configuration. Frequently, these controls were attached to cephalostat for study involving the lower craniofacial feature. Photogrammetric control can be natural features on craniofacial surface such as acne, scar, bite mark and tattoo.

e. Integrating of Photogrammetric Measurement and Laser 3D scanned Model

Surface registration was undertaken to determine the transformation parameters between the 3D laser scan and the photogrammetrically derived surfaces (McIntosh and Krupnik 2002). Theoretically, the two datasets should refer to the same coordinate system. However, the instrumental error and patient movement could introduce a misalignment between the surfaces. McIntosh and Krupnik (2002) argued that a seven parameter conformal transformation could be manually performed using pre-marked anthropometric landmark. The process reduces the errors significantly. Consequently, this study established a set of signalised anthropometric landmarks to provide accurate surface registration.

2.7 Summary

This chapter describes the state-of-the-art of craniofacial imaging system based of photogrammetry and laser scanning technologies. Both technologies were based on the non-contact method and considered to be the most suitable approach for measuring and modeling of craniofacial morphology. Conventional method with calipers required the surgeon to touch the face for the measurement of the related landmarks. Compared to other craniofacial imaging technologies such as computer tomography scan (CT) and magnetic resonance imaging scan (MRI), which employed high radiation for the generation of facial surface, photogrammetry and laser scanning are less radiation effect to facial skin and delivered more safety to human eye (eye-safe).

This chapter ends with the general considerations for the development of *Malaysian Craniofacial Spatial Data Capture Technique*, which is based on photogrammetry and laser scanning technologies.

CHAPTER 3

A PROTOTYPE DESIGN AND DEVELOPMENT

3.1 Introduction

A prototype craniofacial imaging system is developed in this study. The developed system consists of *data capturing system* and *data reduction system*. The details of both systems are discussed below.

3.2 Data Capturing System

The developed data capturing system integrates photogrammetry and 3D laser scanner system. The system also involves the development of the photogrammetric object space control, which consists of craniofacial photogrammetric control frame and patient's chair. Figure 3.1 shows the physical design of the system and Figure 3.2 shows the location of the system in three dimensional views.

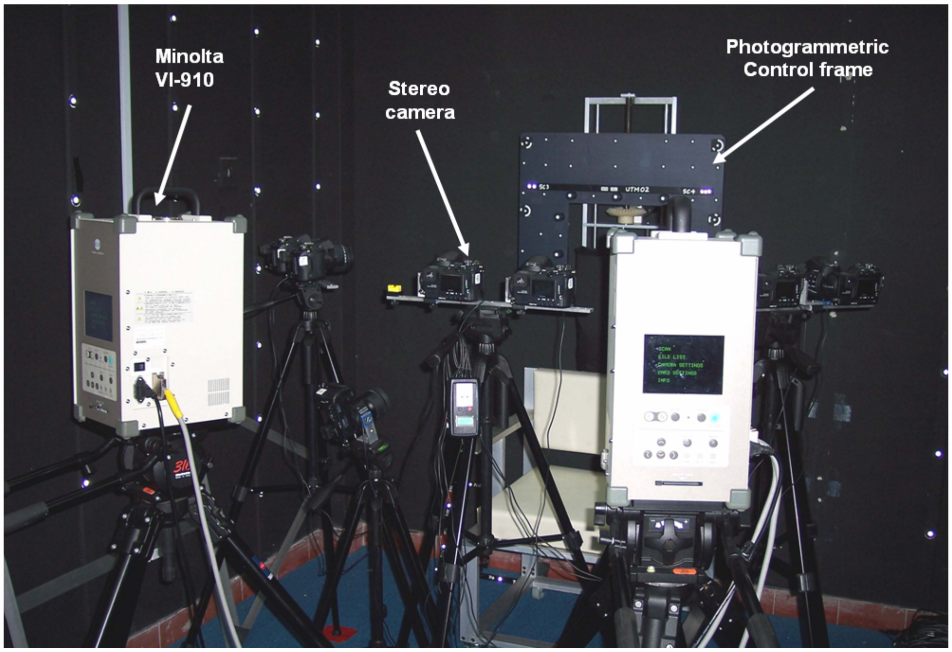


Figure 3.1: Data capturing system – physical design

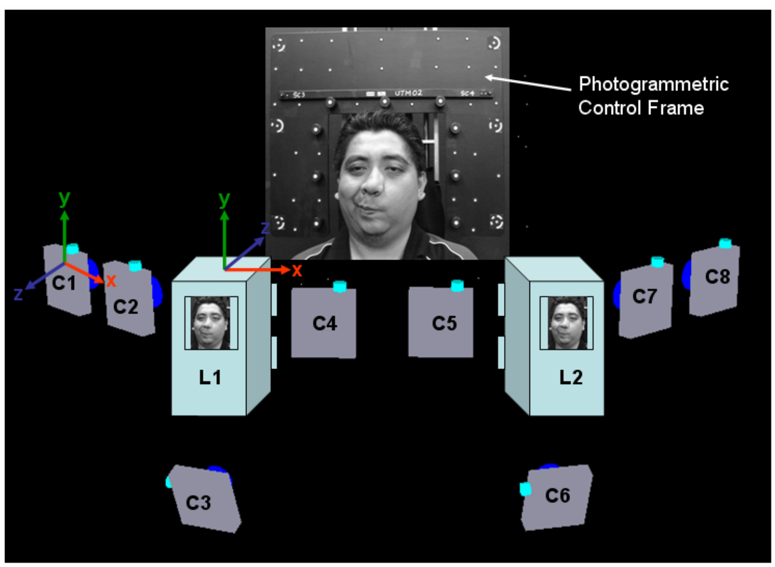


Figure 3.2: Data capturing system – location of the system in three dimensional views

C1 to C8 in Figure 3.2 show the location of the cameras, while L1 and L2 show the location of the laser scanners. The approach implemented in the developed system is unique. Existing and previous data acquisition system for modeling and measuring human faces do not involved the integration or combination of more than one system. Both systems are operated one after another. The detailed information regarding each system is discussed below:

3.2.1 Photogrammetric System

The developed photogrammetric system is shown in Figure 3.3. The objective of having a photogrammetric system is to capture high resolution stereo images of craniofacial surface. The implementation of the system follows the basic stereophotogrammetry operation that has been applied in aerial photo mapping.

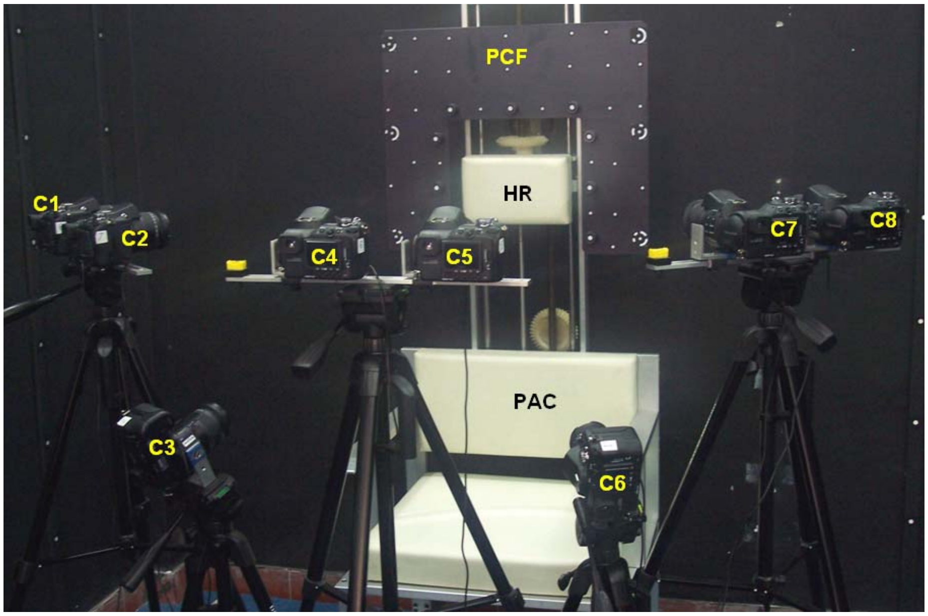


Figure 3.3: The photogrammetric system

The photogrammetric system shown in Figure 3.3 consists of high resolution digital cameras (C1, C2, C3, C4, C5, C6, C7, C8), photogrammetric control frame (PCF), patient's chair (PAC) and head rest (HR). The high resolution digital cameras consists of eight units of Sony CyberShot F828 (8.0 million pixel resolution with CCD format of 6.6mm by 8.8mm – refer Figure 3.4). The camera is selected because of the built in ACC/LANC port which is needed for the synchronization setup. Six of the cameras are setup in stereo mode (C1, C2, C4, C5, C7, C8) to capture craniofacial stereo images and two cameras are setup in roll-diversity convergent mode (C3 and C6) to capture craniofacial convergent images.

(a)

(b)

Figure 3.4: (a) Sony CyberShot F828, (b) Setup of the cameras in stereo mode

Table 3.1 shows the full specifications of Sony DSC F828 professional digital camera.

Table 3.1: Sony Cybershot F828 camera specifications

Imaging Device	*2/3" 8.0 Megapixel Effective Super HAD™ CCD*
CCD Pixel Size	*2.7 μm*
Focal Length	*7.1mm*
Aperture	*f2.0 – 2.8*
CCD Format Size	*6.6mm x 8.8mm (2448 x 3264 pixels)*

The photogrammetric system introduces the external synchronization device to synchronise the shutter of the eight cameras (refer Figure 3.5). The shutters for the eight cameras are released simultaneously. The device enable the cameras to be switched on and off simultaneously.

Figure 3.5: The camera controller and synchronization device

The technical specifications of the photogrammetric system are as below (please refer to Figure 3.3):

a. The configuration of the cameras is based on the combination of multi-stereo and convergent photogrammetric concepts. The output consisted of three sets of craniofacial stereo images and two convergent images.
b. The configuration of the cameras is also based on the "*natural features technique*" which uses craniofacial natural features such as acne, scar and birth marks as control in the absolute orientation process. The configuration enables each natural feature to be digitized in four images. The natural feature that is located on the right part of the craniofacial area is digitised on the images captured by cameras C1, C2, C3 and C4. The natural features that are located on the front part of the craniofacial area are digitized on the images captured by cameras C3, C4, C5 and C6 and the natural features that are located at the left part of the craniofacial area are digitised on the images captured by cameras C5, C6, C7 and C8.
c. The object distance (distance between multi-stereo cameras to patient) is fixed at 700mm. The object distance is determined by the size of the object.

In this case, the size of the craniofacial photogrammetric control frame plus the size of the human head is about 700mm.

d. The stereo camera base distance (the distance between stereo cameras, for example camera C1 to camera C2) is 200mm. Through the base distance, the 70% of stereo overlap (overlapping percentage between images) is achieved with wide angle focal length (7.3mm).

e. The angle between stereo camera C1-C2, the patient and stereo camera C7-C8 is 90^0. The angle between stereo camera C1-C2, the patient and stereo camera C4-C5 is 45^0. The angle between camera C3, the patient and camera C6 is 60^0.

During data collection the patient is asked to sit on the patient's chair with the head placed at the middle of the craniofacial photogrammetric control frame (Figure 3.6). The data collection process takes at least one minute to capture the images per patient.

Figure 3.6: Setup during data collection task

3.2.2 Three dimensional (3D) Laser Scanning System

The basic idea to involve the 3D laser scanning system in the development of craniofacial spatial data is to capture the craniofacial surface model in a fast and high accuracy data capturing mode. The 3D surface laser scanning system is generally designed in two method of operations; time flight method and triangulation method. For short distant scanning case (like scanning human face), most of the 3D laser scanners in the market are designed and built using the triangulation method. The triangulation method is based on triangle concept that linked the laser device, charge couple device (CCD) camera and the scanning object (Figure 3.7 and Figure 3.8).

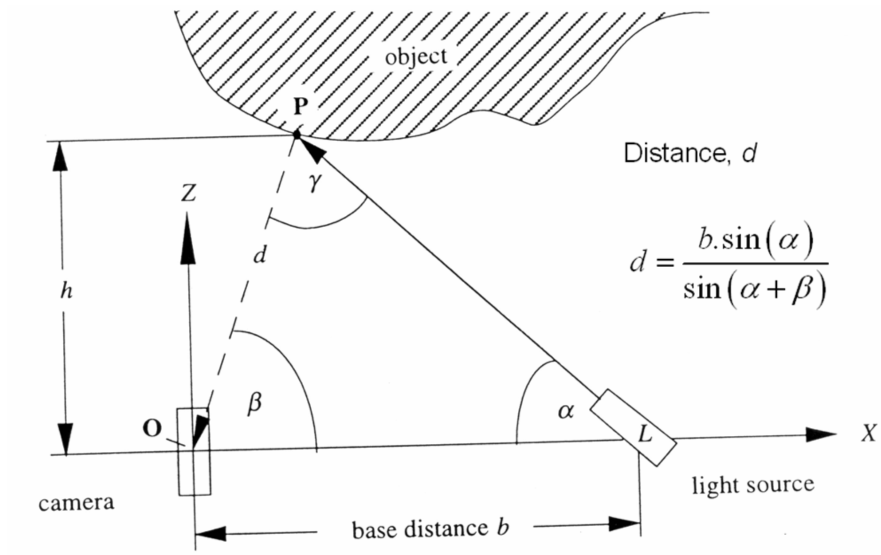


Figure 3.7: 3D laser scanning measurement concept – triangulation method for the calculation of base distance (b)

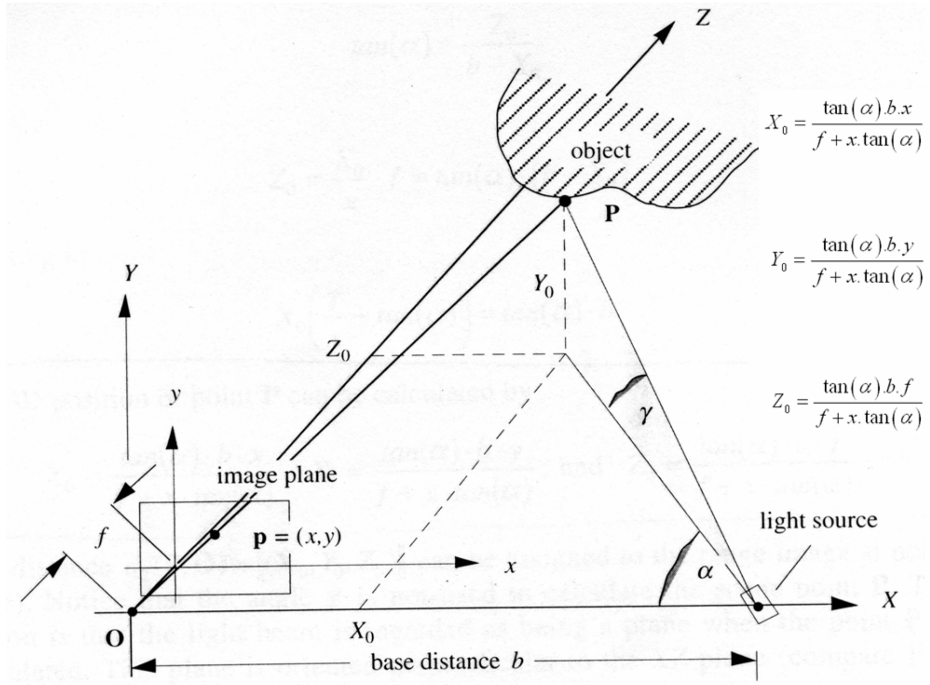


Figure: 3.8: 3D laser scanning measurement concept – triangulation method for the calculation of 3D point clouds

After the initial evaluation of a few laser scanning products, the Minolta VI-910 3D laser scanner (as in Figure 3.9) is selected and two of these scanners are used to scan the whole craniofacial area. Each of these laser scanners emits an eye safe Class I laser (FDA) with $\lambda = 690nm$ at $30mW$ with an object to scanner distance of 600-2500mm. The scanner can be operated in two types of scanning modes; fast mode and fine mode. The fast mode scanning period is 0.3s while the fine mode scanning period is 2.5s. Minolta VI-910 used charge couple device (CCD) camera that can acquire 300,000 3D data points (fine mode scan) and 78,000 3D data points (fast mode scan). The scanner output data is the 3D surface of scanning object with 640 x 480 pixel RGB texture data. The scanner provide three types of CCD lenses with different focal length (f); wide $(f = 8mm)$, middle $(f = 14mm)$ and tele $(f = 25mm)$. The choice of the lens is normally based on the size of the object to be scanned and the object distance. Both scanners are setup at 1000mm from the patient. Table 3.2 shows the important specifications of VI-910 laser scanner.

Figure 3.9: The Minolta VI-910 3D laser scanning system

Table 3.2: Specifications of VI-910 3D laser scanning system

Model	*Non-contact 3D digitizer VIVID 910*
Measurement method	*Triangulation light block method*
Accuracy	*X: ±0.22mm, Y: ±0.16mm, Z: ±0.10mm to the Z reference plane (Conditions: TELE/FINE mode, Konica Minolta's standard)*
Input Time	*0.3s (FAST mode), 2.5s (FINE mode), 0.5s (COLOR)*
Transfer time to host computer	*Approximately 1s (FAST mode) or 1.5s (FINE mode)*
Imaging element	*3D data: 1/3 inch frame-transfer CCD (340,000 pixels)* *Color data: 3D data is shared (color separation by rotary filter)*
Number of output pixels	*3D data: 307,000 (FINE mode), 76,800 (FAST mode)* *Color data: 640 x 480 x 24 bits color depth*
Output format	*3D data: Konica Minolta format (& STL, DXF, OBJ, ASCII points, VRML; converted into 3D data by Polygon Editing Software provided as a standard accessory)* *Color data: RGB, 24-bit raster scan data*

The Minolta VI-910 can operate the scanning job in two modes of measurements either "on-line" mode or "off-line" mode. The "on-line" mode allows the user to control the scanners from the computer via Polygon Editing Tool (PET) software (software that purchased along with the scanner system). The scanning data can be stored directly to hard disk. While the off-line scanning approach allows the user to scan object by using the built in scanning button designed at the back of the scanner and the scanning data was be stored in the memory compact flash card and can be easily downloaded using digital card reader that is available in the market. For the purpose of capturing craniofacial 3D spatial data, the on-line measurement mode was used, because the job is done in the laboratory (Figure 3.10).

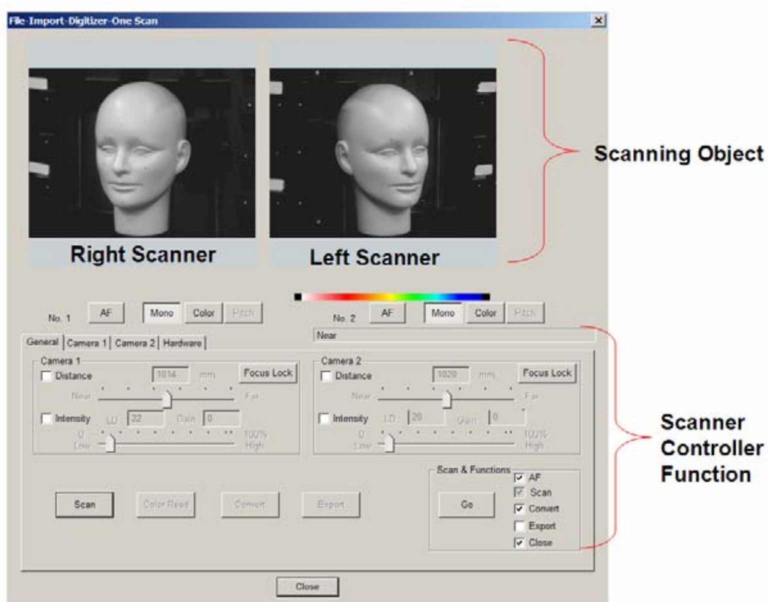


Figure 3.10: "On-line" scanning mode using PET software

The on-line scanning mode offered by the PET software is operated using "Import Digitizer One Scan" interface. The interface window is divided in two parts, namely the view of scanning object and the scanner controller function (Figure 3.10). In the first part, the scanning object from both laser scanners is displayed. The second part allows the user to control both scanners to performed scanning task. If the scanning project required the use of two VI-910s 3D digitizer system, the basic information of both laser scanners is shown in the “Hardware” module (Figure 3.11 and Figure 3.12). The setting of the scanning mode for each laser scanner can also be done by using “Camera 1” and “Camera 2” modules.

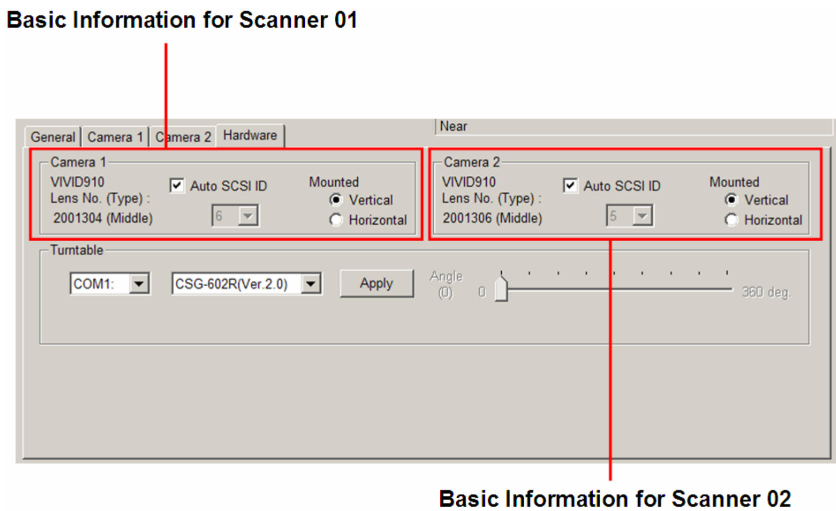


Figure 3.11: Basic information of both laser scanners in the “Hardware” Module

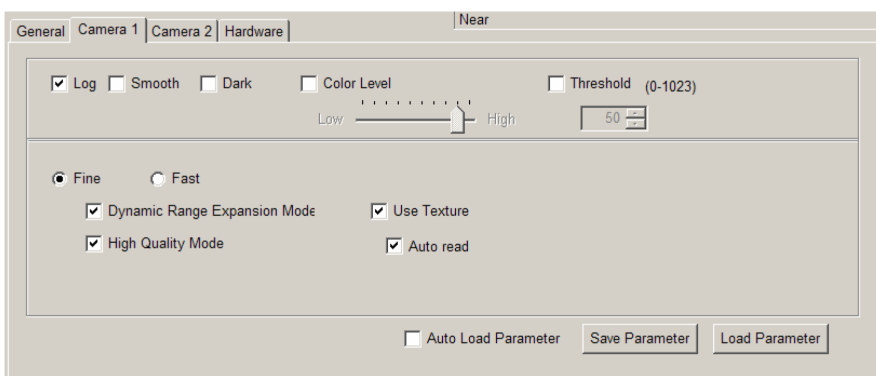


Figure 3.12: The setting of the scanning mode for each laser scanner using “Camera 1” and “Camera 2” Modules.

The interface also provides the preliminary scanning accuracy information by color coding method (Figure 3.13). The function is fully utilized just after the scanning task finished. The accuracy is initially evaluated using the color coding scale which shows the effectiveness of the scanning on the surface of the object.

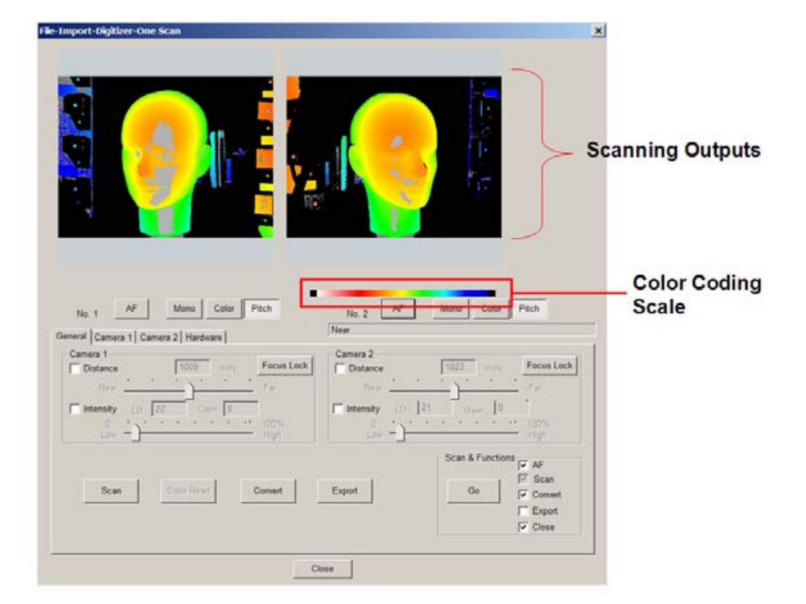


Figure 3.13: Preliminary scanning accuracy information by Color Coding method

3.2.3 Craniofacial Photogrammetric Control Frame

The craniofacial photogrammetric control frame is an important part of the development of craniofacial spatial data capturing system. The craniofacial photogrammetric control frame consists of a special designed chair with adjustable head rest and high accuracy control frame. The control frame is used to provide high accuracy 3D ground control to the stereo images by means of signalized retro-reflective targets. Figure 3.14 shows the perspective view of the craniofacial photogrammetric control frame.

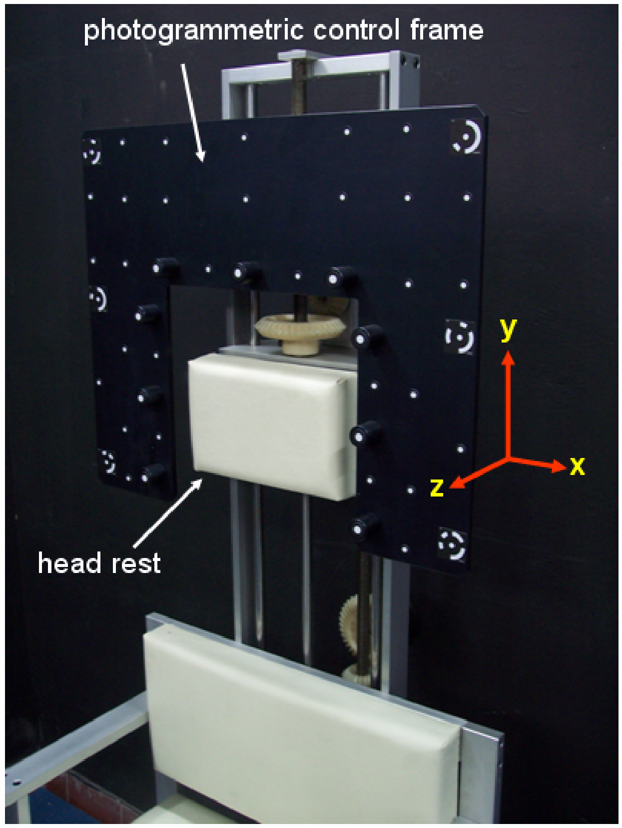


Figure 3.14: Craniofacial photogrammetric control frame

The control frame requires accurate calibration in order to determine the 3D coordinates of the targets. To calibrate the control frame four or more convergent photographs are taken with a high precision invar scale bar placed in the middle of the control frame. A bundle adjustment process is needed to determine the 3D coordinates of the targets. It is not necessary to have any previous known control point in the adjustment as in the case of an absolute orientation of a stereo-model. During data collection process, the patient will sit down on the chair with the head placed at the middle of the photogrammetric control frame. The level of the eye is parallel to x-axis and z-axis (Figure 3.15).

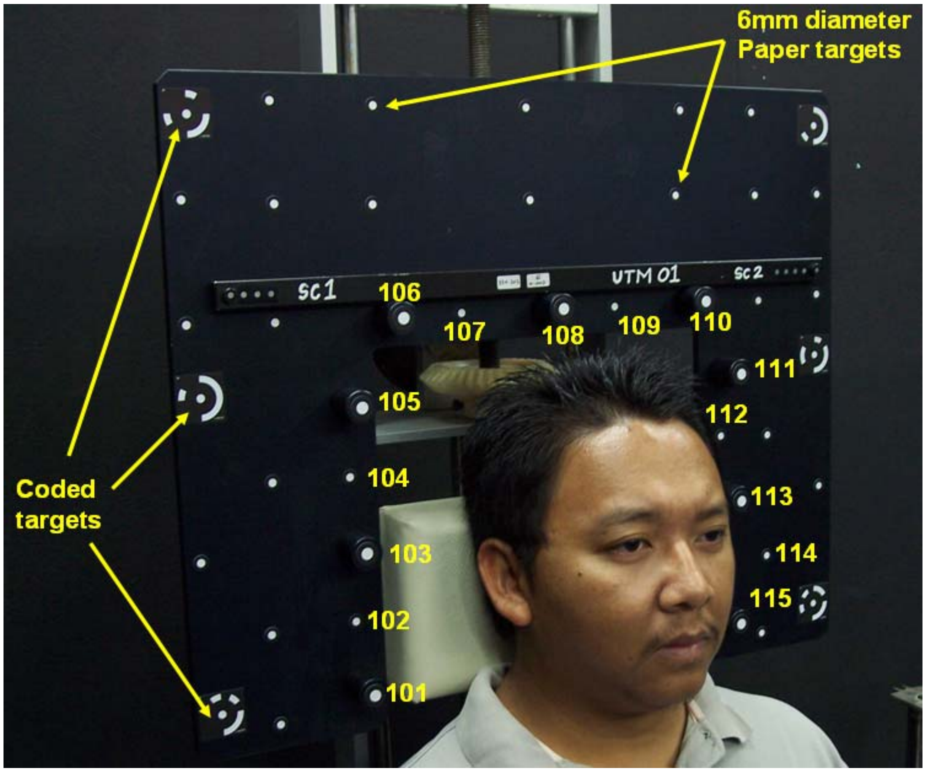


Figure 3.15: The position of patient's head during data acquisition

The photogrammetric control frame consists of 39 control points with 6mm diameter paper targets and 6 photogrammetric coded targets arranged in grid form and well distributed. The paper targets (no 101, 103, 105, 106, 108, 110, 111, 113 and 115) is setup at different depth (60mm depth) from the frame. These situation developed the three dimensional environment in the mapping control. The big number of control points is fully needed to increase the accuracy of relative orientation of the stereo images, where all the points are digitized accurately. The control frame can be moved precisely using built-in moveable gear along the y-axis.

3.3 The Craniofacial Raw Datasets

The data collection task involved the collection of two types of craniofacial spatial data; the stereo images and the 3D laser scan surfaces. This means that for each individual that is involved as samples is photographed using stereo camera and scanned by using the laser scanners. The data collection process is done one after another where most of the cases, the stereo images were captured first because the data collection period of the stereo camera system is very fast (0.2 mili-seconds) as compared to the scanning period which takes about 19 seconds to complete the scanning process from two scanners. A complete datasets will consist of three stereo images, two convergent images and two 3D surfaces (which also known as shells). Figure 3.16 shows the image datasets, while Figure 3.17 shows the laser scanner dataset.

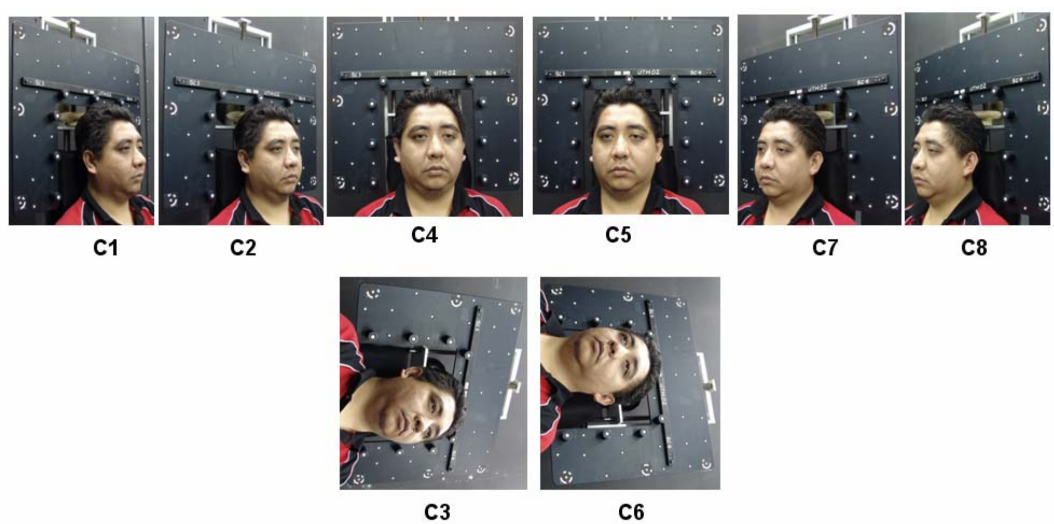


Figure 3.16: Image datasets from camera system

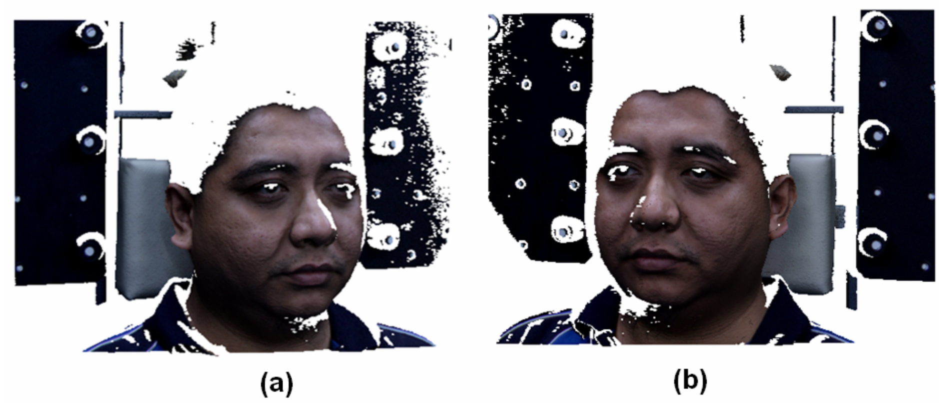


Figure 3.17: 3D laser scanner raw datasets – (a) right shell, (b) left shell

As can be seen in both Figure 3.16 and Figure 3.17, the craniofacial photogrammetric control frame image is included in the raw datasets.

3.4 Craniofacial Spatial Data Reduction System

The data reduction system involves the method used to process the raw data (as captured using data acquisition system). The method used consists of pre and post processing of the raw data. There are two types of data in pre and post processing tasks involved in the project. The first pre and post processing task involved the processing of image datasets (as acquired using camera system), while the second one involved the processing of 3D laser scanner point clouds data. The details of the data processing are as below:

3.4.1 Pre and Post Processing of Images Acquired from the Camera System

The acquired stereo and convergent images involved two pre-processing tasks. The first task involved photogrammetric triangulation process. The aim of the process is to measure the 3D coordinates of the natural landmarks on the craniofacial surface. The 3D coordinates are then used as control points in photogrammetric absolute orientation process (Figure 3.18 and Figure 3.19).

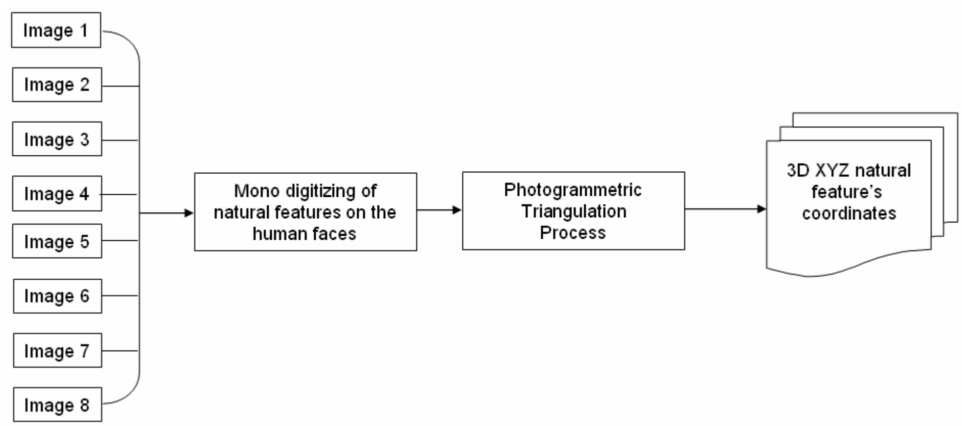


Figure 3.18: The flowchart showing the measurement of natural features 3D XYZ coordinates using Photogrammetric Triangulation process

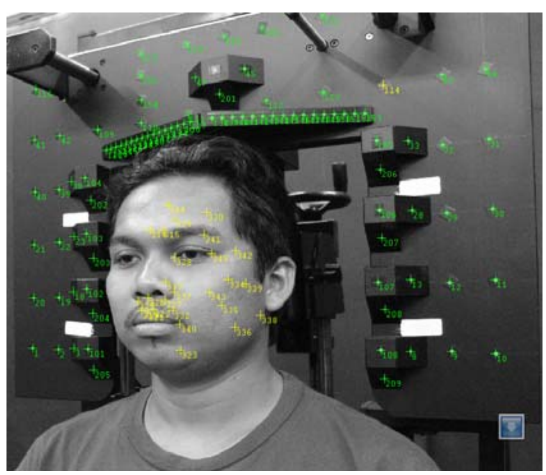


Figure 3.19: Measurement of natural features using convergent photogrammetric method

The stereo images are then proceeds to photogrammetric stereo orientation which involves interior, relative and absolute orientation process to generate the stereo model. The stereo vectorisation are then applied to digitise the three dimensional coordinates of the craniofacial landmarks (see Figure 3.20 and Figure 3.21). The accuracy of the stereo digitising process was evaluated using the RMS value of the absolute orientation. Most of the cases in craniofacial mapping required the RMS value of 0.5mm for X, Y and Z coordinates, respectively.

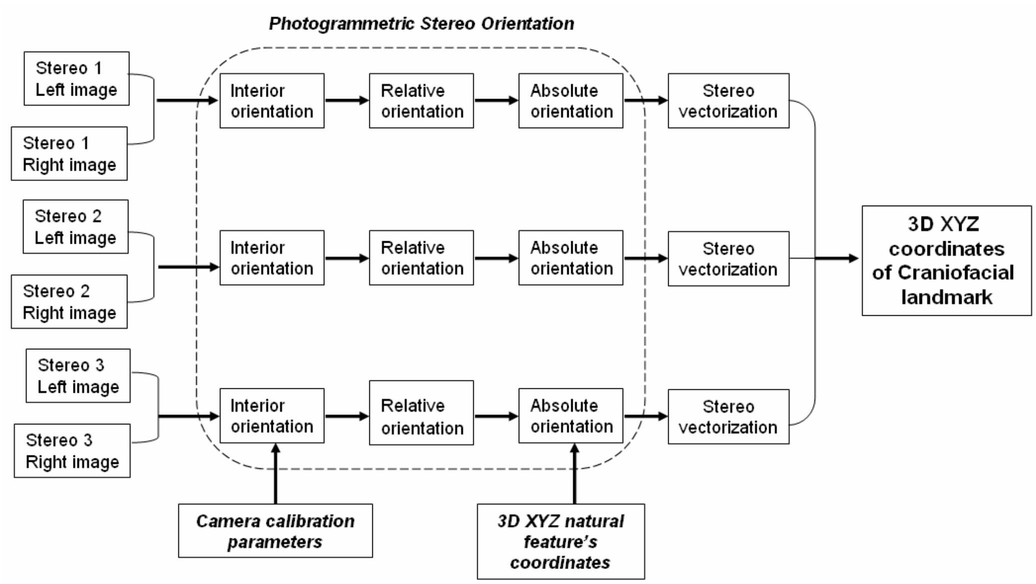


Figure 3.20: The flowchart to show the stereophotogrammetric measurement process of stereo images using DVP Photogrammetric System

Figure 3.21: Post processing of stereo images using DVP system. Note: the 3D coordinate of the landmarks is measured in 3D environment through stereo imaging devices.

3.4.2 Pre and Post Processing of 3D Laser Scanning Datasets

The data processing of the 3D laser scanning datasets involve six common 3D laser modeling process which consist of filtering noise, initial registration and fine registration of the two shells, merging, holes filling and smoothing (as in Figure 3.22 and Figure 3.23). The common processing steps mentioned above ares offered by most of the laser scanning data processing software such as RapidForm 2004 (INUS Technology, Korea) and Polygon Editing Tools (PET) software (Konica Minolta, Japan).

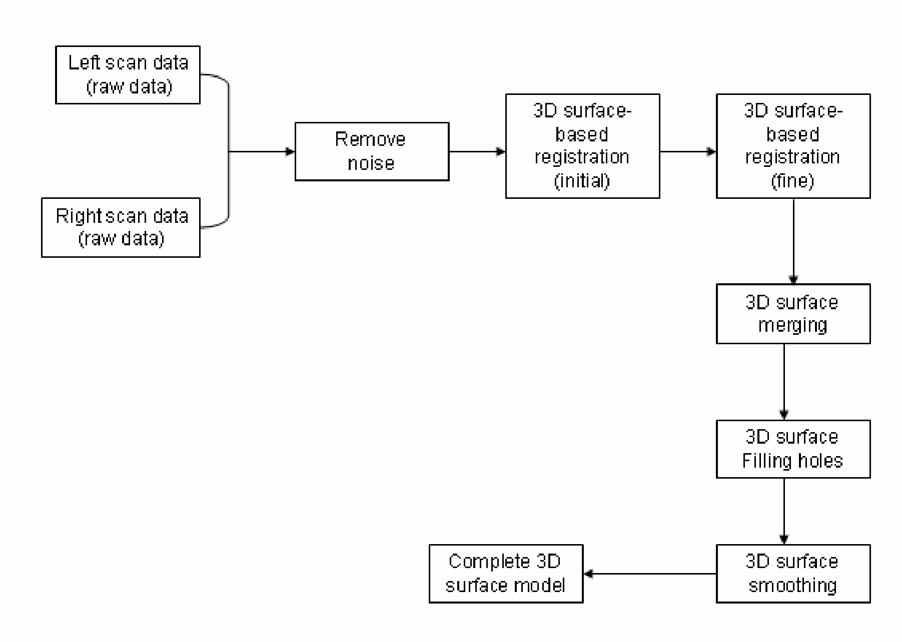


Figure 3.22: The flowchart show the pre-processing steps to process the 3D laser scanning datasets

The post processing involves the measurement of craniofacial landmarks on the 3D craniofacial surface model. The process requires the user to identify the location of the landmarks on the 3D surface based on the terrain (DTM) of the surface and the break-surface, and finally the location is digitised. RapidForm 2004 software offers auto-measure function to measure slope distance, along surface distance and angle between the selected landmarks.

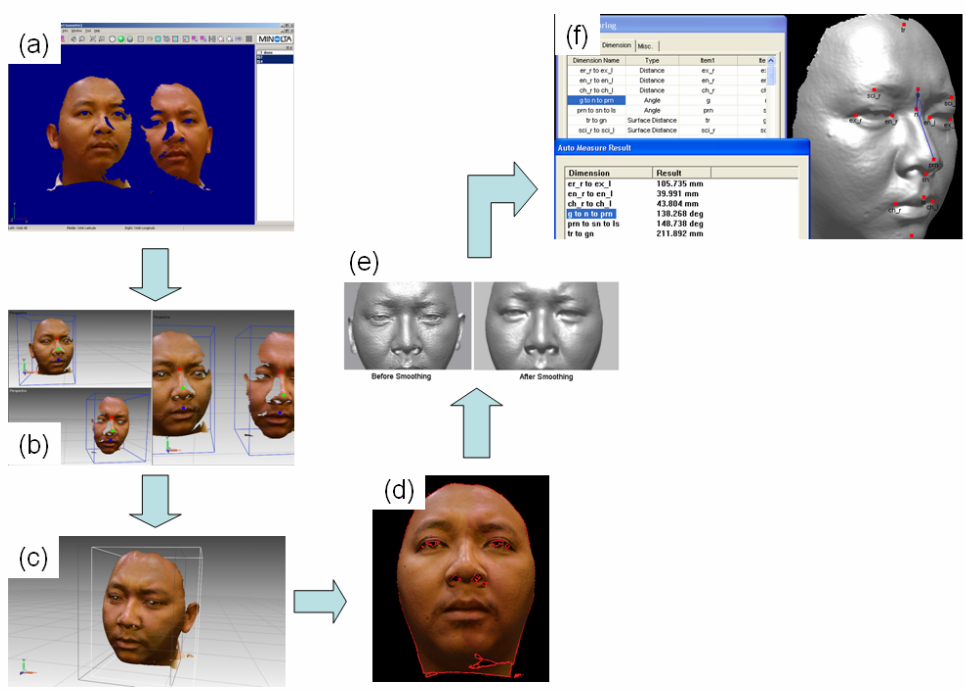


Figure 3.23: Pre and post processing of 3D laser scanning datasets – (a) raw datasets, (b) registration process, (c) merging process, (d) filling holes, (e) smoothing process and (f) measurement of craniofacial landmarks.

3.5 Advantages of a Prototype 3D Craniofacial Imaging System for Craniofacial Soft Tissue Mapping

The developed prototype 3D craniofacial imaging system is the first system developed in Malaysia for the purposes of craniofacial mapping. In terms of 3D measurement of craniofacial soft tissue, the prototype 3D craniofacial imaging system developed in this study offers a non-contact method with high accuracy compared to the conventional method, which used calipers for measuring craniofacial landmarks. Instead of acquiring one type of data which is implemented in most of craniofacial data acquisition system (published in journals), the developed system can be used to acquire two types of craniofacial spatial data which are (a) stereo images of craniofacial soft tissue, and (b) 3D surface model of corresponding craniofacial soft tissue captured in (a). Both data are acquired with patient remain seated for a few seconds. The acquired data (both stereo images and 3D laser surface) are processed using appropriate software and the measurement of the landmarks was successfully obtained in 3D environment in the software, which is similar to conventional method using calipers. The imaging system is fully portable as mobile craniofacial imaging system. These are proven by a series of data collections at USM Hospital in Kota Bahru, Kelantan. The developed system is also automated and easy to operate.

3.6 The Contribution of a Prototype 3D Craniofacial Imaging System to Medical Photogrammetric Field

The main contribution of the prototype 3D craniofacial imaging system to medical photogrammetric field is the development of a new imaging device to improve the accuracy of photogrammetric facial measurements. The imaging device consists of eight professional digital cameras and an intelligent external shutter called “lanc shepherd” camera controller with 0.2 milliseconds synchronization period. The external shutter is battery free and operated using a cameras minimum power. The cameras with high accuracy in synchronisation, is a suitable device to capture human face images with minimum effect of the movement error of the face.

CHAPTER 4

SYSTEM CALIBRATION

4.1 Introduction

This chapter describes the system calibration method. The system calibration involved with the calibration of eight Sony CyberShot F828 digital cameras, the calibration of Minolta Vivid 910 laser scanner and the calibration of the purposed built photogrammetric control frame. The calibration also involves the photogrammetric system accuracy testing, the camera synchronization testing and the calibration of the laser scanning critical factors related to craniofacial mapping.

4.2 Calibrating the Camera

The purpose of camera calibration is to determine the calibration parameters such as the camera focal length, the principal point coordinates, the radial distortions of the lens, the tangential distortion of the lens and the un-flateness of the CCD sensor. In this study, the eight Sony CyberShot F828 digital cameras are successfully calibrated using self-calibration technique. A calibration device which allows the constant object distance to be maintained is used in the calibration test (Figure 4.1). The position of the camera mount and the target board are adjusted so that the object distance of 700mm would be similar to the object distance of the craniofacial stereo photography. The focal length of the each camera is set to a wide angle setting of 7.1mm. The zoom ring is taped securely so that the focal length is fixed for the entire test. The camera aperture is set at f/2.0 to ensure the use of the fast shutter speed during data captures. The camera is positioned in the camera mount and the target board is photographed with a high precision invar bar placed in the middle of the board. The target board is rotated 90^0 to allow four convergent photographs to be taken. In addition, the camera is rotated around its z axis by 90^0 to allow four more convergent photographs to be taken. For reliability analysis, five sets of eight convergent photographs are obtained for the test. All the convergent photographs are digitized automatically using Australis camera calibration software. A self-calibration technique is used to perform bundle adjustment process.

Figure 4.1: The camera calibration device

4.3 Calibrating the Photogrammetric Craniofacial Control Frame

The photogrammetric craniofacial control frame is calibrated to determine the coordinates of the signalized targets. To calibrate the control frame four sets of six convergent photographs are taken with a high precision invar scale bar placed in the middle of the frame (Figure 4.2). The bundle adjustments process is carried out using Australis software to determine the coordinates of the signalized targets. The mean of four sets of coordinates is used to provide object space photogrammetric control for 3D mapping of craniofacial photographs.

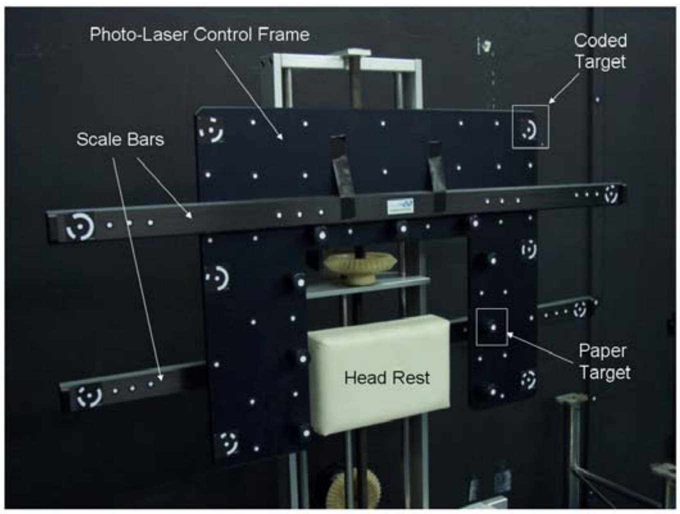


Figure 4.2: Calibration of the photogrammetric craniofacial control frame

4.4 Photogrammetric System Accuracy Testing

The calibration of photogrammetric system is completed with an accuracy testing of the system for measuring craniofacial landmarks. The system accuracy test is carried out using mannequin and finally the system is tested on real-life human faces as test objects (Majid et al (2005) and Majid et al (2006)). The digital photogrammetric workstation (DVP system) is used to carry out the stereo digitizing process as the craniofacial landmarks are difficult to locate monoscopically.

4.4.1 Preliminary Test

The purpose of doing the preliminary test is to verify the work that has been done by other researchers in measuring craniofacial landmarks using stereophotogrammetric method. The preliminary testing involved the used of the targets on the photogrammetric craniofacial control frame as control for stereophotogrammetric absolute orientation. The method is known as *"Control Frame Method"*. The test is carried out using mannequin with signalized targets (Figure 4.3). The signalized target is used as the test points. However, tests show that recommended location on the control targets on the frame is not suitable for high accuracy stereo-orientation. The accuracy in the Z (along the optical axis) does not satisfy the project requirement accuracy of 0.7mm. The problem appeared because of the control targets are too far from front facial surface. Consequently, the accuracy of the z differs between the left face and the front model and the worst accuracy of 2.0mm for the latter. The problem is solved by using natural features on the face, such as scar, acne and birth mark.

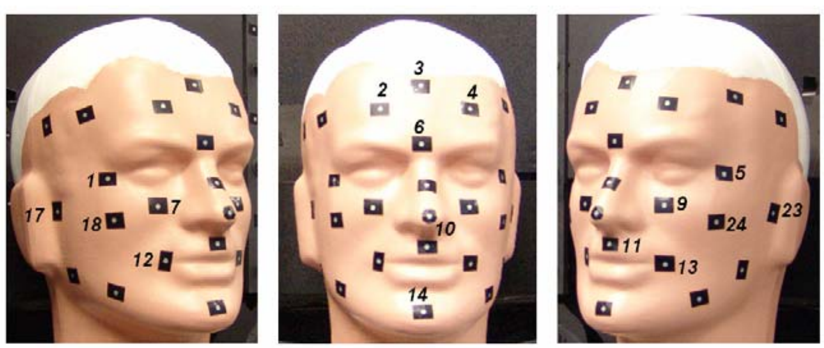


Figure 4.3: Mannequin with signalized targets

A method is developed to obtain accurate coordinate of the natural features. It involves a bundle adjustment of images from the three stereo-models and two convergent images using the control frame targets. The bundle adjustment computes the coordinate of the natural features. Subsequently, the natural features are used to carry out absolute orientation of the stereo-models. The method is known as *"Natural Features Method"*.

4.4.2 Test on the Mannequin

The similar mannequin (Figure 4.3) is used to carry out the test. The test involves the data collection and data processing tasks. The details of the test are as below:

4.4.2.1 Data Collection

The photography consists of two stages: (a) a set of convergent photographs of the mannequin to determine coordinates of the simulated natural points (see Figure 4.4) and (b) a set of six stereo-photographs of the mannequin for stereo-digitizing of the anthropometric marks and 3D surface (see Figure 4.5 and Figure 4.6). In stage (a), six convergent photographs are captured. Stage (b) involves the capturing of 60% stereophotogrammetric overlap of the mannequin from three different stereo camera positions which covers the craniofacial area. The lens to object distance is 600 mm.

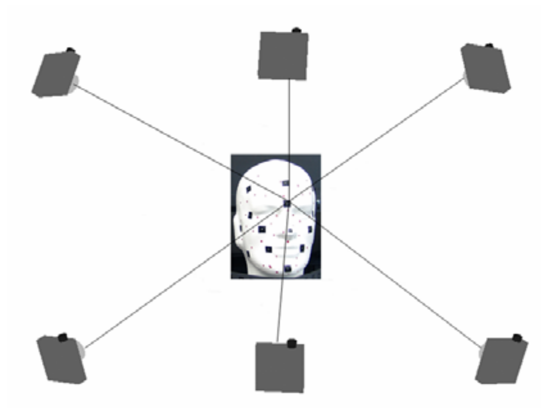


Figure 4.4: Convergent photographs for the bundle adjustment of the test point coordinates. Note that the photographs may not be used for stereo-digitizing on Photogrammetric workstation.

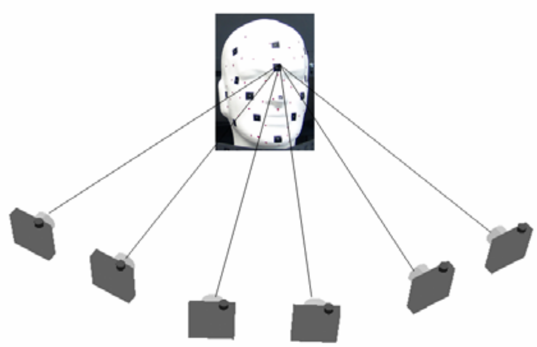


Figure 4.5: Stereo-photographs for stereo-digitizing of the anthropometric marks. Note the camera configuration and the bundle of rays to the natural point and test points.

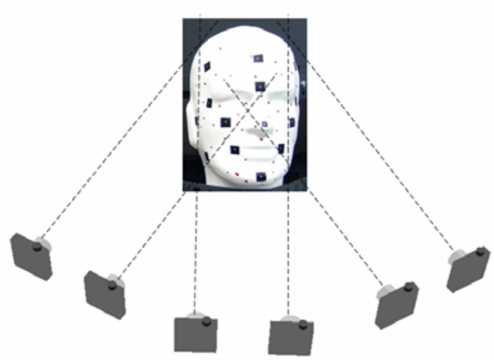


Figure 4.6: The stereo photographs of the test object showing the overlap areas.

4.4.2.2 Data Processing

a. Obtaining high accuracy object-space coordinates of control points.

Australis photogrammetric software (Department of Geomatics, University of Melbourne, Australia) is used to mono-digitize image coordinate (x and y) of the retro-targets on the control frame and test points on the six convergent photographs. The retro-targets of the scale bar are also digitized. A bundle adjustment is performed on the image coordinates of the digitized points using Australis. As only one camera is used in the capture of the images camera parameters are not fixed in the adjustment. The scale bar is used in the adjustment to scale the object-space coordinate. The output of the adjustment is a set of accurate coordinates for the control and test points.

b. Obtaining object-space coordinates of the natural points.

Mono-digitizing is also performed on the stereo-photographs. However, natural points are added to the list. The scale bar targets are not observed because the object-space would be scaled by control-frame coordinates which are obtained in Stage I. A bundle adjustment is performed on the image coordinates of the observed points. It must be noted that a triangulation would be performed if there are very few observed points and the camera parameters (c, Xp, Yp, K1, K2 and k3) of the six cameras would have to be fixed in the adjustment to achieve a Least Squares solution.

c. Obtaining object-space coordinate of test points using stereo-digitizing technique.

The Stereo Orientation module, DVP software (DVP, Canada) is used to establish stereo-orientations (interior, relative and absolute) for stereo-digitizing and the vectorization module is used to obtain the three-dimensional coordinate of the test points (Figure 4.7). In this study, the stereo images (front view, left view and right view) are processed separately. Each stereo image involves two different three-dimensional ground controls for absolute orientation; (a) by using signalized targets established on the control frame and (b) by using the signalized targets established on the facial surface (representing the natural points). For each process, the three-dimensional coordinates of the test points is measured three times stereoscopically and the average of the coordinates is calculated.

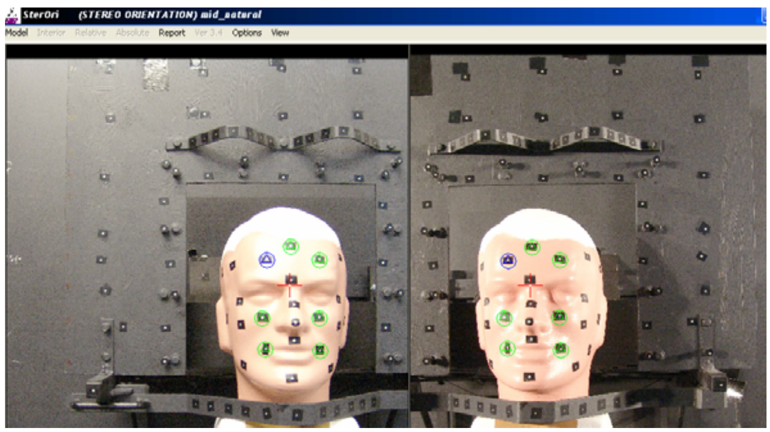


Figure 4.7: Stereo digitizing of test points using DVP software.

d. Obtaining distances between test points using caliper technique.

The digital caliper with the accuracy of 0.1mm is used to measure directly the distances between the selected test points on the craniofacial surface. The caliper is calibrated where the value of zero (0) is always started at the accurate scaling designed on the caliper. Each distance is measured three times and the average of the distances is calculated. Figure 4.8 shows the digital caliper used in the measurements.

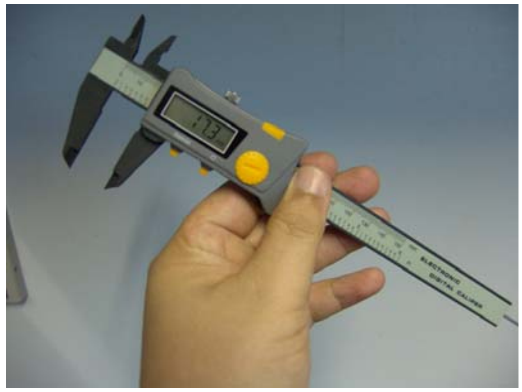


Figure 4.8: A digital caliper used for direct measurement on the mannequin

4.4.3 Test on the Real Life Human Faces

In order to verify that the natural features method is really accurate to support the craniofacial anthropometric job, a real life facial surface with signalized targets (representing natural features and the test points) is used as test object (see Figure 4.9). The face is posed at the middle of the control frame and is photographed using the photogrammetric system. The photogrammetric triangulation method is used to calculate the three dimensional coordinates of the signalized target accurately using Australis software. Both control frame and natural features methods is applied separately in the photogram metric absolute orientation of three pairs of stereo models. Nine linear measurements are performed between the signalized targets. The direct measurements are also performed using caliper as a comparison with the control frame and natural features methods. All the measurements are repeated three times in order to make sure that each method is reproducible.

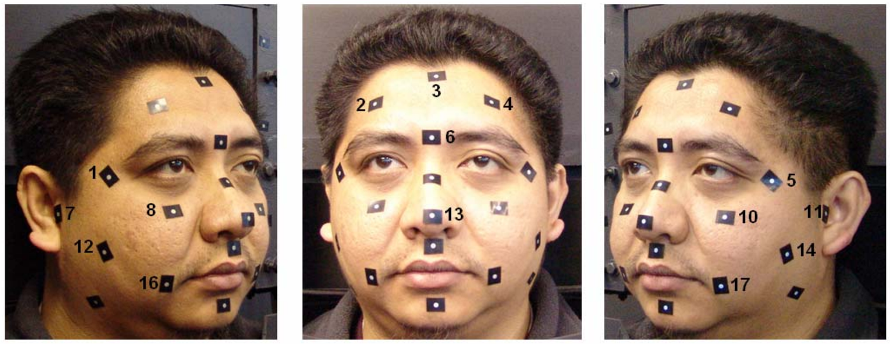


Figure 4.9: Real human face with signalized targets to represent the natural points and test points.

For final evaluation of the natural features technique, the technique is tested on the real-life human face without having any signalized targets to represent the natural features. Six selected natural features is used as test points and are accurately measured by photogrammetric bundle adjustment (Figure 4.10). The 3D coordinates gained from the bundle adjustment method is selected as reference values. At the same time the similar selected natural features is measured using natural features and control frame techniques. The 3D coordinates of both techniques (acquired from stereo measurements) are than compared with the 3D coordinates gained from bundle adjustment. The root mean square error (RMSE) value of the 3D coordinate differences is than calculated.

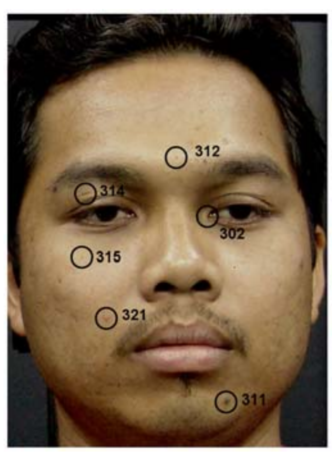


Figure 4.10: Selected natural features as test points

4.5 Camera Synchronization Testing

For the purpose of applying stereophotogrammetric method to medical application such as craniofacial mapping, the synchronization of all the related stereo cameras is a very important factor. Therefore, the synchronization test is compulsory. The purpose of camera synchronization test is to evaluate the capability of the electronic device to activate the camera shutter simultaneously. From the study, it is possible to find out whether the lack of synchronization of the cameras could have adverse effects on the accuracy of craniofacial spatial data. We can also find out the optimum errors in the displacement, which will contribute toward the total error in the craniofacial data.

The plumb line method is used in the camera synchronization test. The plumb line is setup in front of the photogrammetric control frame. The control frame coordinates will be used as a control to measure the displacement of the test point mounted on the plumb line. Figure 4.11 shows the plumb line test device.

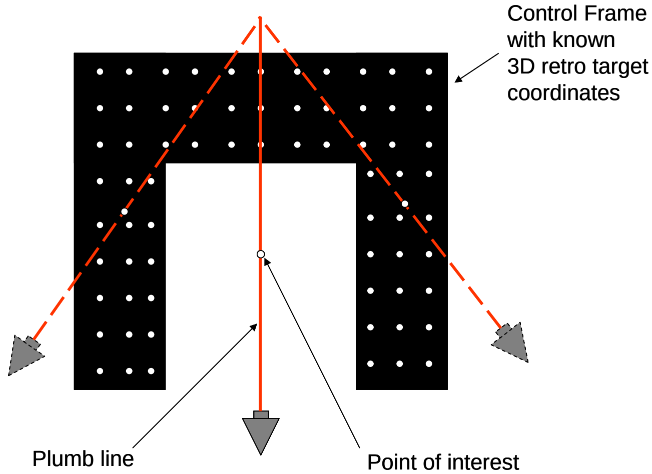


Figure 4.11: Plumb line test device with target as point of interest

As mentioned earlier, the synchronization test will determine how good the synchronization of all the cameras used in the stereophotogrammetric system. By using the control frame coordinate system, the 3D coordinates of the test point can be determined. Camera 1 as shown in Figure 4.12 will be considered as the fast camera and selected as reference. The coordinate of the test point will be calculated using triangulation method in Australis software which compares image from camera 1 with cameras 2, 3, 4, 5, 6, 7 and camera 8. The output of this test is the sets of 3D coordinates of the test point. For accurate synchronization of all the cameras, the calculated 3D coordinate of the test point must be similar in X, Y and Z value. The displacement between the coordinates is considered as an error in the synchronization process.

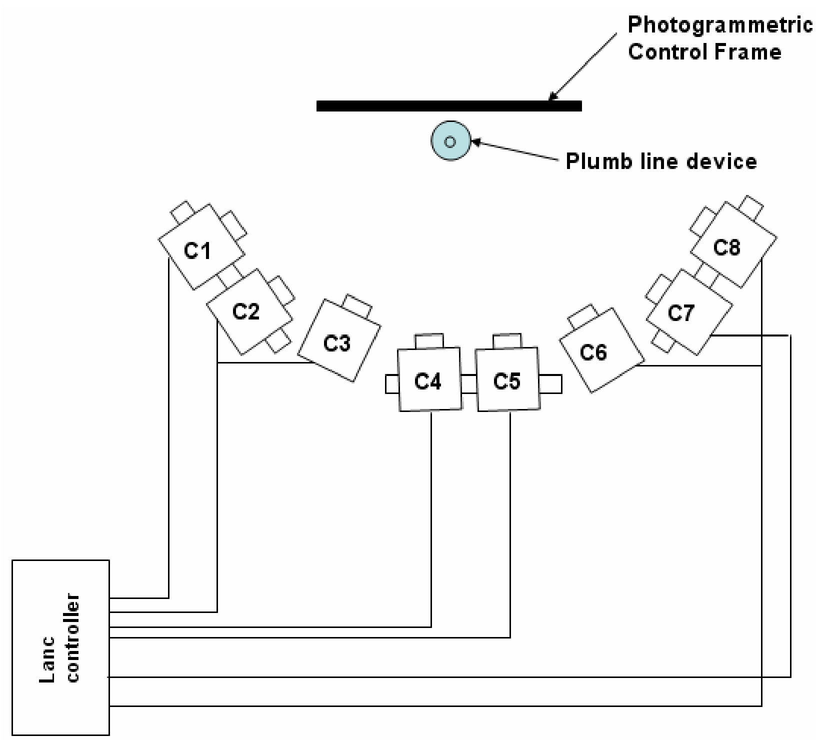


Figure 4.12: Camera synchronization test setup

4.6 Calibrating the Laser Scanner

The Vivid 910 is calibrated using three objects of different shape, size and texture: 1) a small cylinder; 2) dental cast; and 3) a mannequin. Subsequently, the objects are measured by close-range photogrammetry technique and a Microscribe 3D electronic digitizer system (Immersion Corporation, San Jose, CA) where applicable. The measurements obtained by the scanner are compared with the measurements obtained by both the close-range photogrammetry and Microscribe 3D digitizer system (Figure 4.13). The close-range photogrammetry measurements are selected as true values.

Figure 4.13: Microscribe 3D digitizer

4.6.1 Scanning the Cylindrical Object

A cylindrical object of width of 120mm and height of 196mm is chosen because of the simplistic curve-shape and smooth surface (Figure 4.14). The object is scanned five times and the averaged width and height are computed.

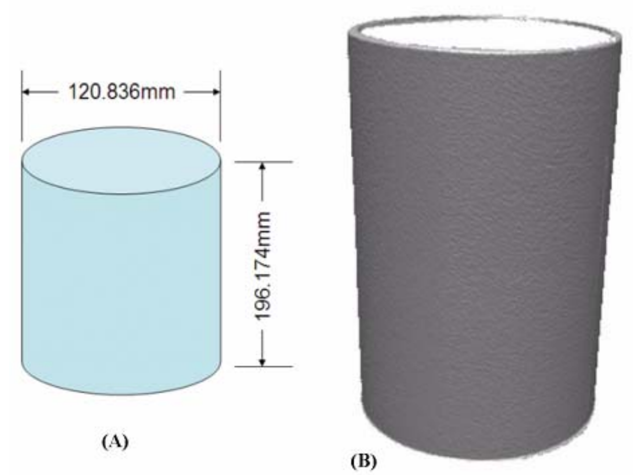


Figure 4.14: The cylindrical object: (A) is Drawing and (B) Laser Scan.

4.6.2 Scanning the Dental Cast

The dental cast is positioned at 650mm (S_d = *650mm*) from the scanner (Figure 4.15). A telephoto lens (focal length = 25 mm) which is used as the dental cast is small as compared to regular objects like a human trunk. To build a complete 3D model two scans are required and the optical axis of the scan are set roughly to 25 degrees from the central line as shown in the figure.

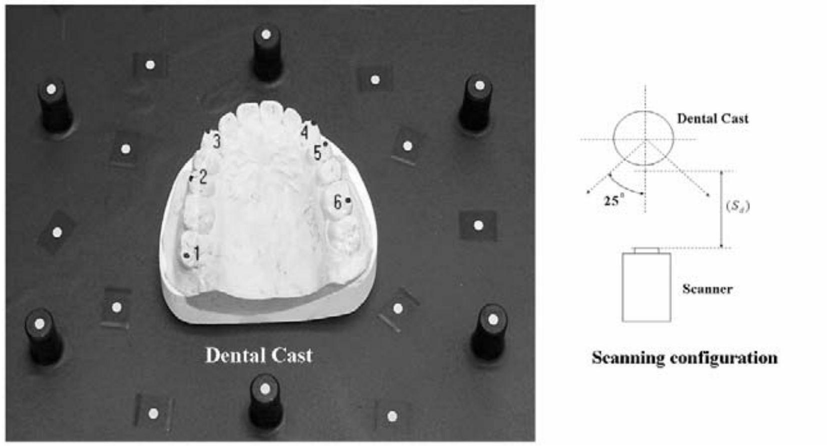


Figure 4.15: The dental cast and the scanning configuration

The scanning is followed by a pre-processing involving a 3D registration of the two scans (known as shell) to build a complete 3D model. The registration method uses a reverse engineering method programmed into the RapidForm 2004 3D modelling software (INUS Technology, Seoul, South Korea). Five corresponding points is measured manually on the left shell and the right shell respectively. The digitizing of the five points is followed by the registration which proceeds automatically. Figure 4.16 shows the 3D registration process.

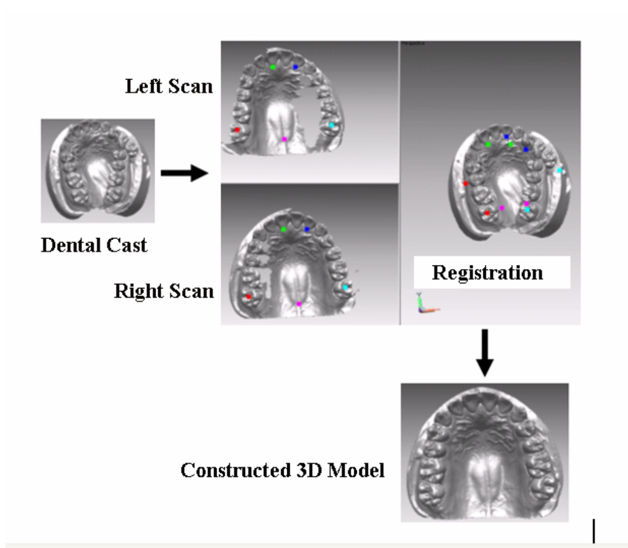


Figure 4.16: 3D shell/shell registration using Rapidform Software

The accuracy of the 3D registration process is analyzed using shell/shell deviation method. The method calculates the deviation value between the left shell and right shell dental in the overlapping area of the dental cast. The deviations between the shells are displayed in colour scale method (Figure 4.17). The colour scale shows the registration accuracy is close to 0.1mm (average value of deviation).

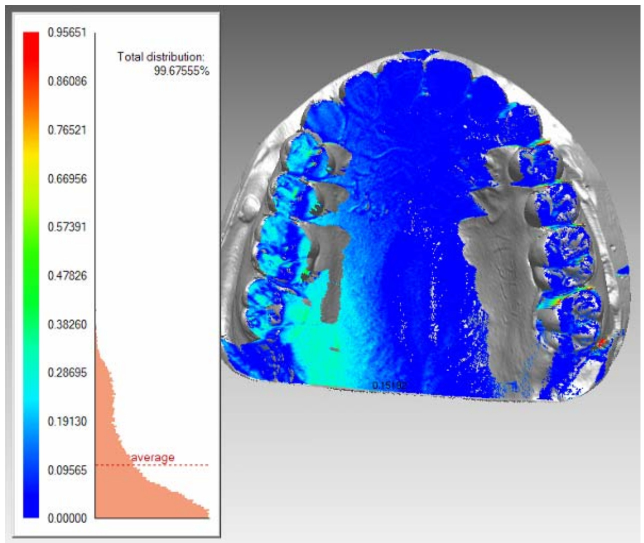


Figure 4.17: Shell/Shell deviation analysis of rebuilt dental cast surface model

The final step in the processing of the scans is the 3D merging process. The 3D merging process could be executed if the accuracy of the 3D registration of the left shell and the right shell is within the accuracy required for the project. The accuracy required for the mapping project is 0.7mm and the value is larger than the 3D registration accuracy (0.1mm). The 3D merging process is again carried out using RapidForm software. The merging process involves combining the two overlapping shells into one shell or one 3D surface model. Figure 4.18 shows the merged dental cast model.

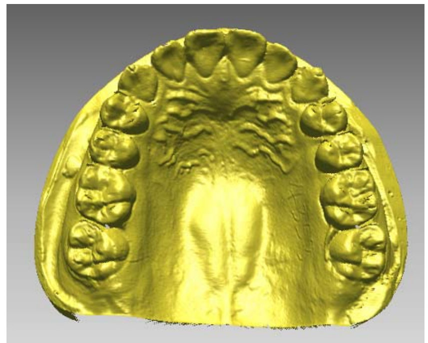


Figure 4.18: Merged 3D dental cast

The accuracy of the 3D dental cast is evaluated by a comparison of the slope distances between anatomical dental points. Six anatomical dental points are selected (Figure 4.15). Ten slope distances is measured on the 3D model using point-to-point distance measurement function (RapidForm software). The average slope distances obtained from five constructed models are compared with the distances from convergent photogrammetric technique and the Microscribe 3D electronic digitizer system. Figure 4.19 shows an example of the slope distance measurement on the dental cast surface 3D model.

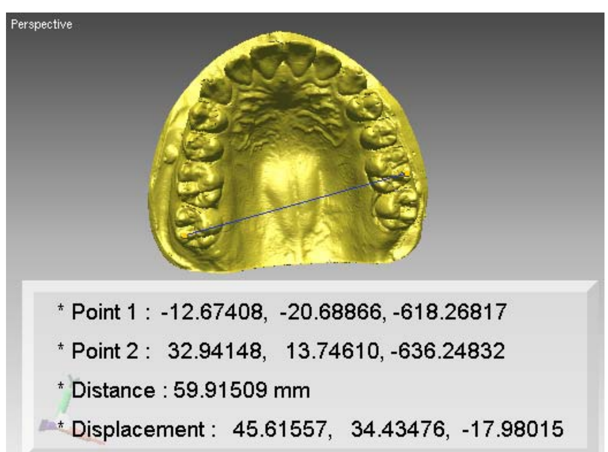


Figure 4.19: Slope distance measurement on dental cast surface 3D model

As mentioned elsewhere in section 4.6, measurements from the photogrammetric technique are selected as the true values. Consequently, it is essential to provide a short discussion as to the method of imaging, data capture and accuracy analysis of this technique. The object provided is based on the dental cast which is considered difficult to map because of its size. The dental cast is placed on top of a calibration range as shown in Figure 4.20. The range consists of retro-targets which can be digitized to one-hundredth of a pixel. The range is calibrated before the exercise (Chong 1999). Three sets of six-convergent images is captured and processed using Australis bundle adjustment software (Photometrix Pty Ltd, Kew, VIC. Australia). The average of the 3D coordinates of the anatomical dental points is used to calculate the distances between the points (Figure 4.15).

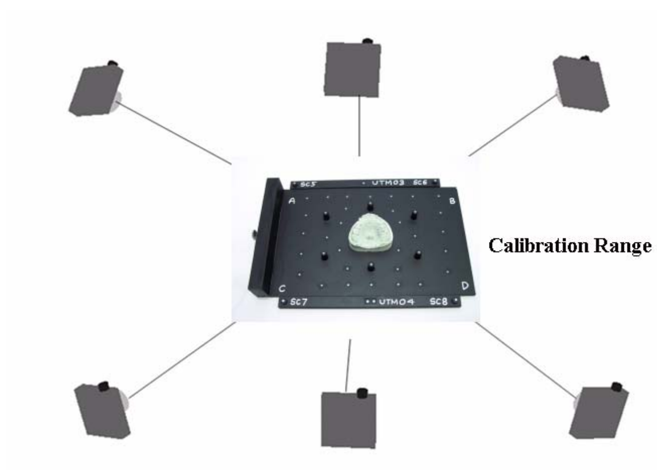


Figure 4.20: Measurement of dental cast using convergent photogrammetric method

4.6.3 Scanning the Mannequin

The mannequin and the scanner are positioned as shown in Figure 4.21. Nine anthropometric marks are placed on the mannequin so that slope distances can be obtained from the scanned model for accuracy comparison. The mannequin is scanned three times and each time both the left and the right scans are captured.

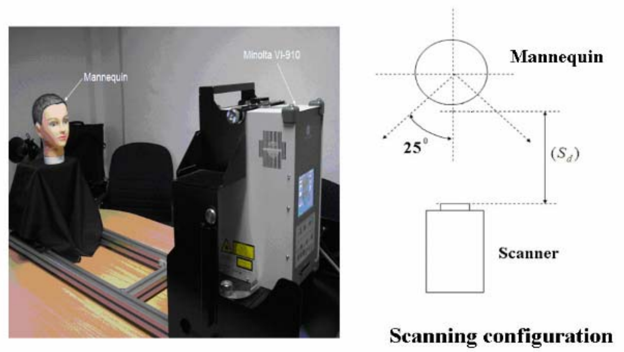


Figure 4.21: The mannequin and the scanner during the scanning. (Note that the holding device can rotate the scanner along it vertical axis)

4.7 Calibrating the Laser Scanner Critical Factors

This section describes the details of the tests of studying the Minolta VI-910 laser scanner based on a few important technical factors which are considered to affect the accuracy for human craniofacial mapping. A list of these factors considered is as follows:

- Scan distance (S_d) and camera focal length (f),
- Scan resolution (R),
- Scan intensity (I),
- Number of overlapping scan per craniofacial area (N), and
- Scan angle (α).

Tests are carried out using the custom-built "bench-top-frame" device (Konica Minolta, Japan, Figure 4.22). The VI-910 laser scanner is positioned as shown in the figure while the mannequin can be moved forward and/or backward using a sliding-plate along a set of steel rail. Various scan distances can be set up for the test.

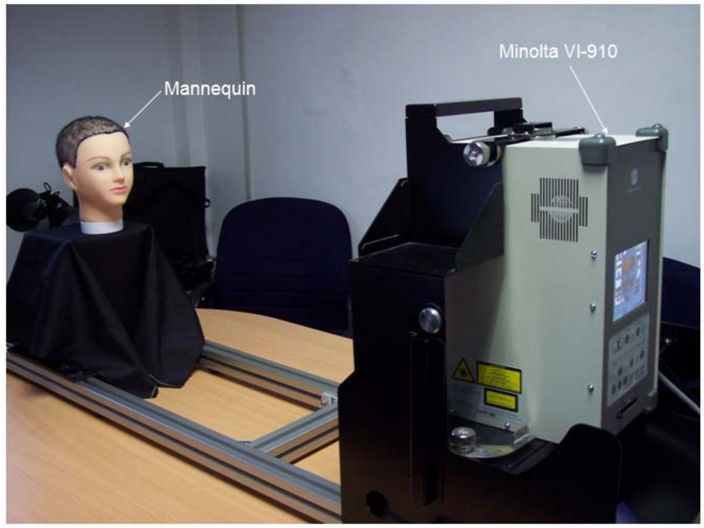


Figure 4.22: Setup of the tests using custom-built device

4.7.1 Optimal Scan Distance and Camera Focal Length

The objective of this study is to find the optimal scan distance (distance from laser scanner to the subject) for scanning human craniofacial area. The study also involved the finding of the correct lens to use. Minolta VI-910 scanner provides three types of lens: namely, wide-angle (f = 8 mm); middle-angle (f = 14 mm); and telephoto (f = 25 mm). A range of scan distances are used and they are 700mm, 800mm, 900mm and 1000mm. The scan distances are based on the findings of previous works on the human craniofacial mapping conducted by the authors (Majid *et al.* 2005). A minimum scan distance of 700 mm is needed to cover the scan area using the middle-angle lens. The wide-angle lens and middle-angle lens only are used in the tests. The telephoto lens is not selected because it is usually used for scanning small objects, such as dental cast, and often at a very short scan distance. According to the manufacturer, the telephoto lens can be used to scan bigger object, but that will require long scan distances (>1000 mm) to obtain optimal coverage of craniofacial area.

To mimic a human craniofacial object, a mannequin is marked with black dots which represent craniofacial landmarks. Three sets of scan are performed for each scan distance, and the mannequin is rotated to the left 45°, 0° and to the right 45° for each set so that a complete model of the craniofacial area can be obtained (Figure 4.23). Subsequently, three sets of 3D surface model of the mannequin are generated by precise registration and merging process of each set of three scans using Rapidform 2004 software (INUS Technology, Seoul, South Korea). Slope distances between the landmarks are measured using 'point to point measure' function of the same software. These distances are compared to the distance obtained by Microscribe 3D digitizer system (Immersion Corporation, San Jose, CA). The calibration of the Microscribe digitizer is not discussed in this report.

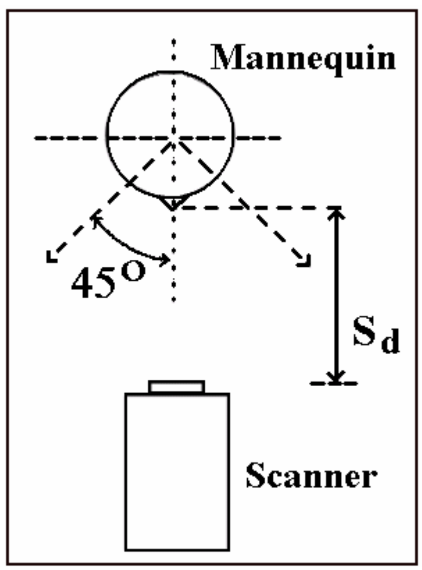


Figure 4.23: Setup of the scan distance test. Note that S_d is Scan distance

4.7.2 Laser Intensity

The maximum power of the Laser is considered eye-safe by the manufacturer. The concern is the effect of the beam intensity on the accuracy of the scanned data. By observing the laser beam of various intensities (numerical value on display) one can see the 'blooming' effect of the beam. Blooming enlarges the beam width. Consequently, the beam intensity must have adverse effects on the texture and accuracy of the captured 3D spatial data. The test is designed to determine the optimal intensity of the laser beam required to obtain high quality data (spatial and texture) of the craniofacial surface. A mannequin resembling human skin texture is selected for the test. The mannequin is scanned at various laser intensity values as shown in Figure 4.24. Similar to the previous test, the slope distances obtained from the test are compared with the distances gained from Microscribe 3D digitizer system.

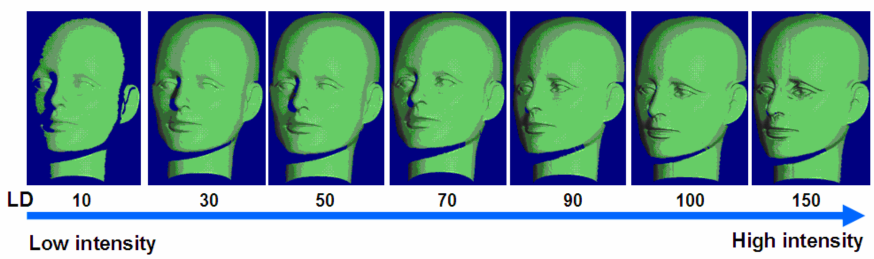


Figure 4.24: Laser intensity in numerical values.

4.7.3 Scanning Resolution

Minolta VI-910 3D digitizer provides three classes of scanning resolution, namely: 1) low resolution (fast mode); 2) medium resolution (fine mode with one scan) and 3) high resolution (fine mode with three scans). These scanning modes produce different density of 3D point clouds and different texture resolution (Figure. 4.25). Tests are carried out using the three scanning modes to scan the craniofacial area of the mannequin and the process is repeated twice to ensure high quality data are captured for analysis.

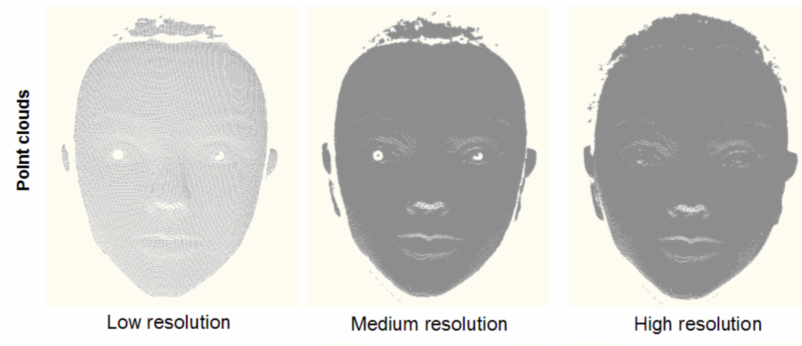


Figure 4.25: Scanning resolution. Note the density of point clouds and texture quality.

4.7.4 Number of Overlapping Scan for the Craniofacial Area

The purpose of the test is to determine the optimal number of overlapping scan required to obtain high quality complete 3D surface model of craniofacial area. In general, a complete 3D model of the craniofacial area covers the surface from left ear to right ear and from the hair line to bottom part of the chin. To obtain a complete surface model of craniofacial area, the number of overlapping scan is considered an important factor for both efficiency and accuracy. The test involves the acquisition of two sets of scans as described below (Figure 4.26):

- Three overlapping scan: the front view, the left and the right views of the mannequin, and
- Two overlapping scan: the left and the right views of the mannequin.

Overlapping scans are registered and merged to obtain a complete surface of the craniofacial area using Rapidform software. The evaluation of the test involved the measurements between craniofacial landmarks, marked as black dot on the mannequin. The slope distances obtained from the test are compared with the distances gained from Microscribe 3D digitizer system.

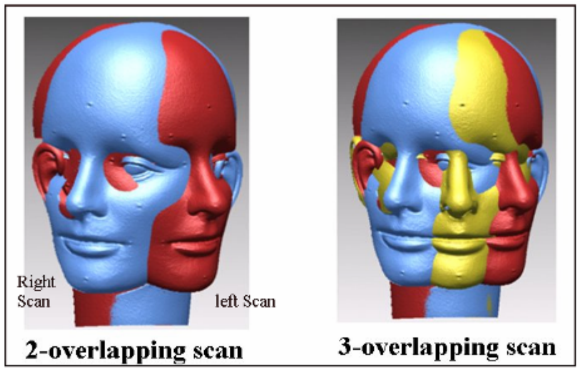


Figure 4.26: Two and three overlapping scan configuration.

4.7.5 Scan Angle

The test determined the optimal scan angle (α) for setting the scanners to capture the craniofacial area (Figure 4.26). The scan angle is defined as twice (2x) the angle subtended between the vertical plane bisecting the head along the nose and the optical axis of the scanner camera lens. A set of scan angles ranging from 20° to 140° at 20° intervals is used. In addition, the scan distance is fixed at 700 mm (based on previous test results discussed elsewhere in the paper). The aim of the study is also to determine the camera optical geometry which will give the best results when two scanners are used together. The optical geometry can be a representation of the base (b) and (S_d) or (α) as shown in Figure 4.27.

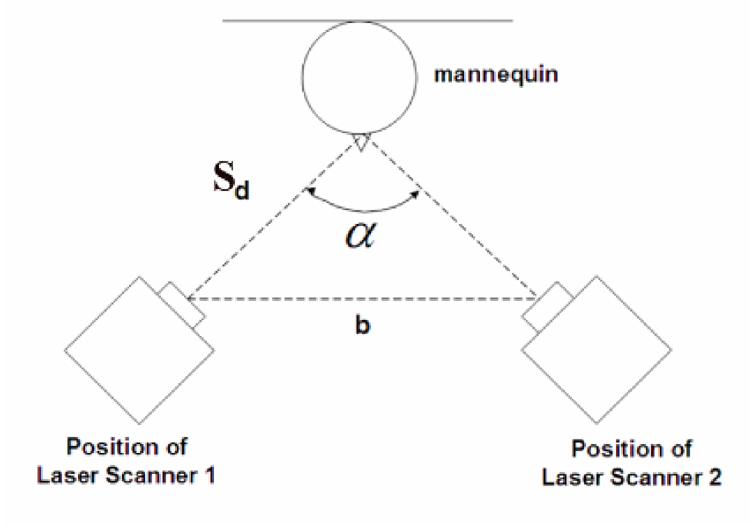


Figure 4.27: The setup for evaluating the scan angle (α).

The scan from both scanners for each test angle is registered and merged using the Rapidform software. Again, slope distances of the landmarks are compared to the ‘true’ slope distance. In addition, the registration accuracy of each scanning angle is evaluated using shell/shell deviation method. The shell/shell deviation technique is an analysis of the quality of the registration and merging of two adjacent overlapping scans and the technique may be used to evaluate the closeness of fit of two similar 3D surfaces (obtained from different view point or different epoch) of the same object.

4.8 Summary

This chapter discusses the method used to calibrate the craniofacial imaging sensors (cameras and laser scanners). The sensors are calibrated separately using different test objects and methods. The methods is also developed to evaluate the accuracy of the photogrammetric system to measure craniofacial landmarks and to evaluate the synchronization of the cameras in capturing craniofacial images. The system calibration chapter is ended with the complete study of the critical factors that influence the laser scanner (which is focused on Minolta Vivid 910) to the craniofacial mapping.

CHAPTER 5

INTEGRATION AND REGISTRATION OF PHOTOGRAMMETRY AND LASER SCANNING SYSTEM

5.1 Introduction

This chapter describes the details of the alignment process of 3D craniofacial point cloud datasets through photogrammetric targets method. The needs for precise alignment of the point clouds using the photogrammetric targets method is essential and become the excellent alternative to solve the alignment problem when the scanning angle is increased and the lack of the corresponding features on the scanning datasets are happened. As shown in Figure 5.1, it is difficult to digitize the corresponding features because the features are not accurately modeled by the laser scanners. Both models is failed to align and the error of the alignment process is shown in Figure 5.2.

In this study the existing procedures of the alignment process through the photogrammetric method is enhanced to improve the accuracy of the final 3D craniofacial model.

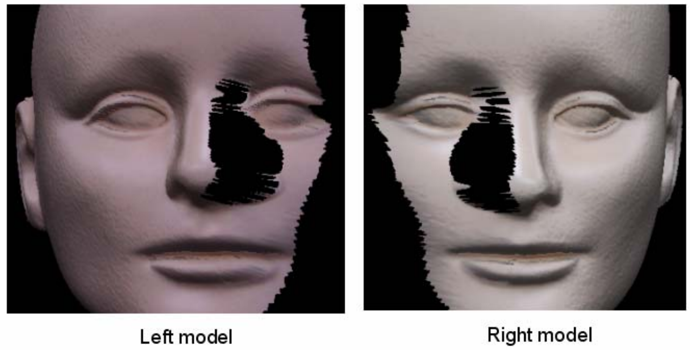


Figure 5.1: The lack of corresponding features on 3D laser scanner surface model

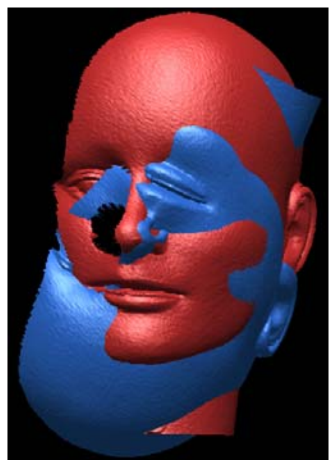


Figure 5.2: Error in 3D alignment process – effect from the lack of corresponding features to perform the complete alignment process

5.2 The Photogrammetric Targets Alignment Method

The photogrammetric targets alignment method differs from other 3D alignment method, for example the corresponding features method which is implemented in almost all the 3D point cloud processing software (RapidForm 2004 software and others). The corresponding method requires the user to digitize at least three corresponding features before performing the initial and fine alignment process using the Iterative Closest Point (ICP) method (as shown in Figure 5.3 and Figure 5.4).

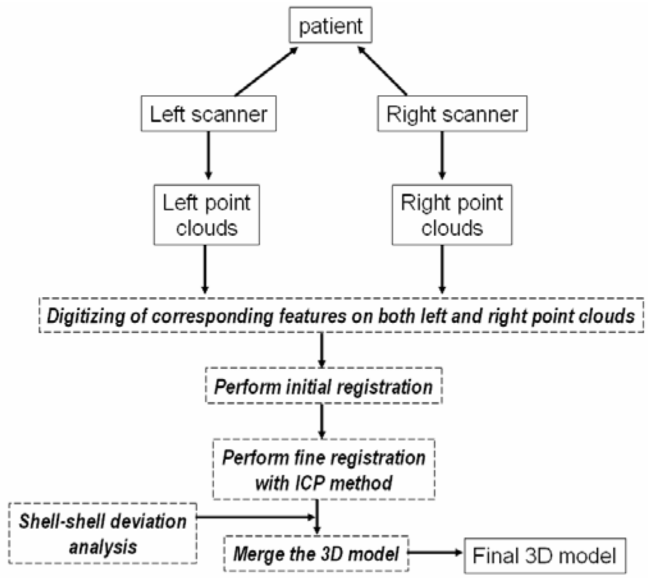


Figure 5.3: The corresponding features method for the alignment of point clouds (as practice in the RapidForm 2004 software)

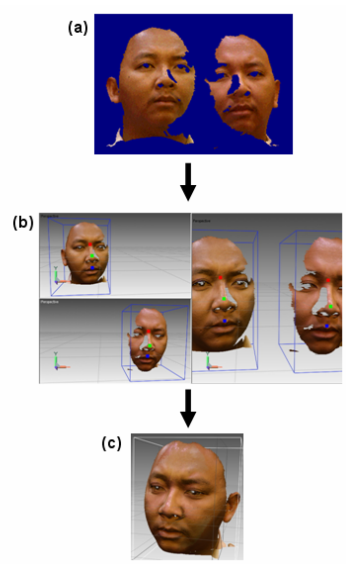


Figure 5.4: The corresponding features method - (a) scan datasets, (b) the alignment process and (c) the merged 3D model

The corresponding features method requires the scanning datasets to be in real texture format. This is because the texture information will help the user to accurately identify the exact location of the corresponding features on the 3D model.

The 3D alignment of point clouds through photogrammetric targets method used in the overlapping photogrammetric targets, in the scanning area, as the alignment component to perform the alignment process. The photogrammetric target is measured accurately using the bundle adjustment method to determine the 3D coordinates of the targets in photogrammetric coordinate system. The overlapping photogrammetric targets is also accurately digitized using sub-pixel targets location method on the scanning images that has been captured by the built-in CCD camera in the scanner. The 3D coordinates of the digitized targets on the scanning images is defined in laser scanning coordinate system. The coordinates are then transformed to photogrammetric coordinate system using 3D conformal transformation method. The 3D point clouds are successfully aligned after the transformation process and are stored in ASCII format. The output is known as pre-merged point clouds (as shown in Figure 5.5).

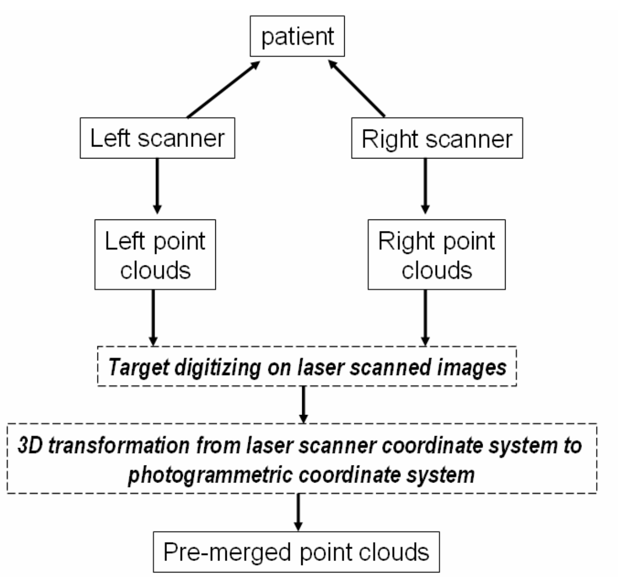


Figure 5.5: Alignment of point cloud using photogrammetric targets – the existing practice

Figure 5.6 show the additional process that has been implemented in the photogrammetric targets alignment method in order to improve the accuracy of the pre-merged point clouds. The output from the photogrammetric targets alignment method is pre-merged with 3D model in point clouds form, even though the raw scanning datasets contain the 3D texture and 3D mesh datasets. In order to generate the 3D surface model, the pre-merged point clouds require pre-processing task. The pre-processing task includes the point clouds filtering (filter point clouds noise) and 3D triangulation process. In the point clouds filtering task, the point clouds outliers is deleted using the filter noise module in the RapidForm software. The 3D triangulation process is used to re-generate the 3D surface mesh model of the scanning object. The ICP method is successfully employed in the alignment process and the merged model is analyzed using shell-shell deviation method. The final 3D model of the scanned object is successfully generated.

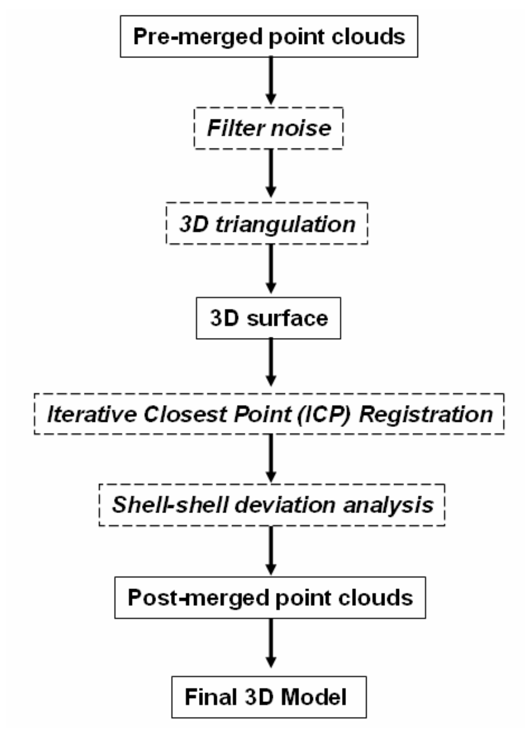


Figure 5.6: Alignment of point cloud using photogrammetric targets – the additional process to improve the 3D alignment process

5.3 Setup for the Craniofacial Mapping

For the purpose of craniofacial mapping, which requires non-contact rule of the craniofacial area for the measurement of craniofacial landmarks, the overlapping photogrammetric targets is setup on the special built photo-laser control frame (as shown in Figure 5.7 (a). The process starts with the calibration of the "photo-laser control frame". The "photo-laser control frame" consists of close-range photogrammetric paper targets (as shown in Figure 5.8). The control frame is designed to have differences in depth value by using 30mm diameter cylindrical rod attached on the plate. Four coded targets are stacked on the plate for automatic calibration process. Two scale bars with coded and paper targets are used to supply scaling on the measurements. Fifty convergent images (normal and roll views) are captured using Minolta A200, eight million pixels digital cameras within 1 meter object distances.

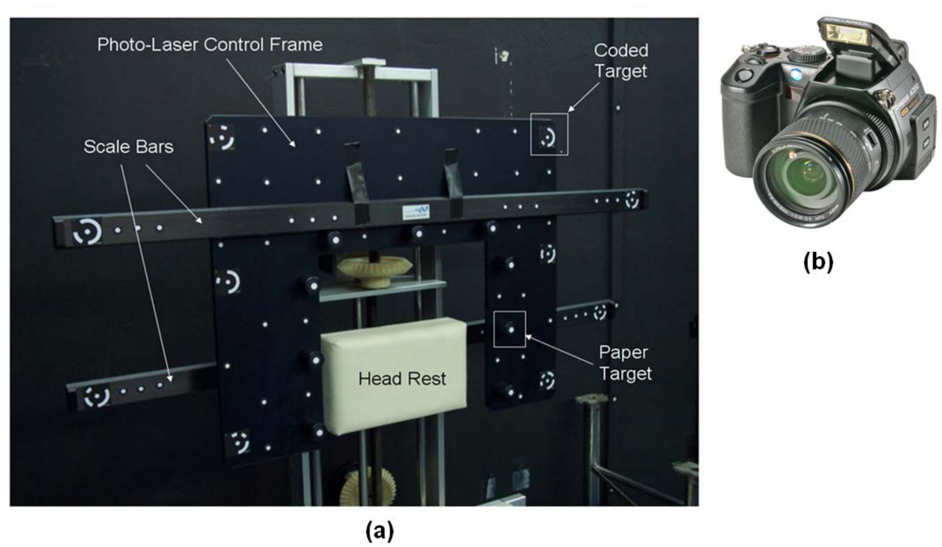


Figure 5.7: (a) The "Photo-Laser Control Frame" – setup during the calibration process, (b) Minolta A200 digital cameras

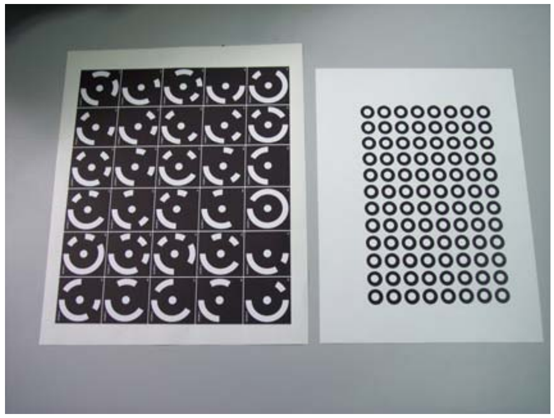


Figure 5.8: The photogrammetric coded and paper targets used in the photogrammetric targets alignment method

The photogrammetric image processing (using IMetric Software System) starts with relative orientation (RO) measurements to predict the preliminary 3D coordinates of the targets. By using coded targets, the RO processes allows automatic measurement of the targets in each images. The bundle adjustment method is finally performed to refine the 3D coordinates of the targets. The overall accuracy of measured 3D coordinates is 0.018mm, 0.025mm and 0.028mm for X, Y and Z, respectively. The targets are then used as a control for the 3D alignment process of the point clouds datasets. Table 5.1 shows the X, Y and Z coordinates of the targets.

Table 5.1: X, Y and Z coordinates of the targets

ID	X (mm)	Y (mm)	Z (mm)
101	0.002	0.003	0.019
102	-0.687	51.274	-30.204
103	-0.893	110.668	-0.159
104	0.0578	164.102	-30.271
105	0.449	219.943	0.006
106	36.191	283.565	0.034
107	98.412	282.899	-30.105
108	172.714	283.384	-0.018
109	238.626	280.888	-30.162
110	309.640	283.023	0.017
111	345.989	219.661	-0.050
112	346.036	162.864	-30.269
113	345.739	109.570	-0.052
114	342.323	51.062	-30.228
115	345.460	0.007	0.010

The second step of the case study involves with the scanning process of the test objects using Minolta VIVID 910 three-dimensional laser scanners. The case study involves with two test objects; (a) the mannequins and (b) real-life human faces. Both test objects is placed at the middle of the photo-laser control frame. The mannequin is used to determine the accuracy, reliability and error in the proposed method. The test on real-life human face involves with the scanning of ten normal faces. Figure 5.9 shows the location of the photogrammetric targets used in the test and Figure 5.10 shows the position of the human head during the test.

Figure 5.9: Location of photogrammetric targets used in the study

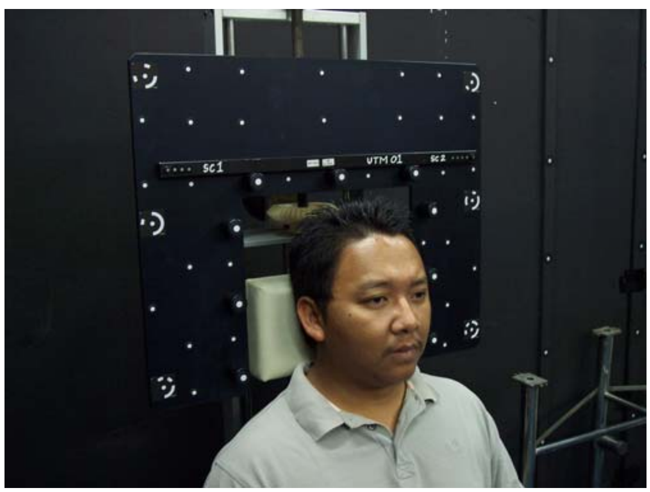


Figure 5.10: Position of the real-life human head during data capture

5.4. The Pre-Processing of Laser Scanning Datasets

The input data for the alignment process is the 3D coordinate of the targets (determined by photogrammetric method) and the laser scanner point clouds datasets (cdm format). The cdm format consists of two laser scanner data, the 3D point clouds and the color images taken by the CCD camera (built-in the laser scanner system). For the purpose of measuring the targets in laser scanner data, the colour images are used and the sub pixel target measurement method is applied. The centroid of the photogrammetric targets in the images is similar centroid on such targets in point clouds datasets. Figure 5.11 shows the pre-processing tasks involved in the development of final craniofacial 3D model using the proposed precise 3D alignment method.

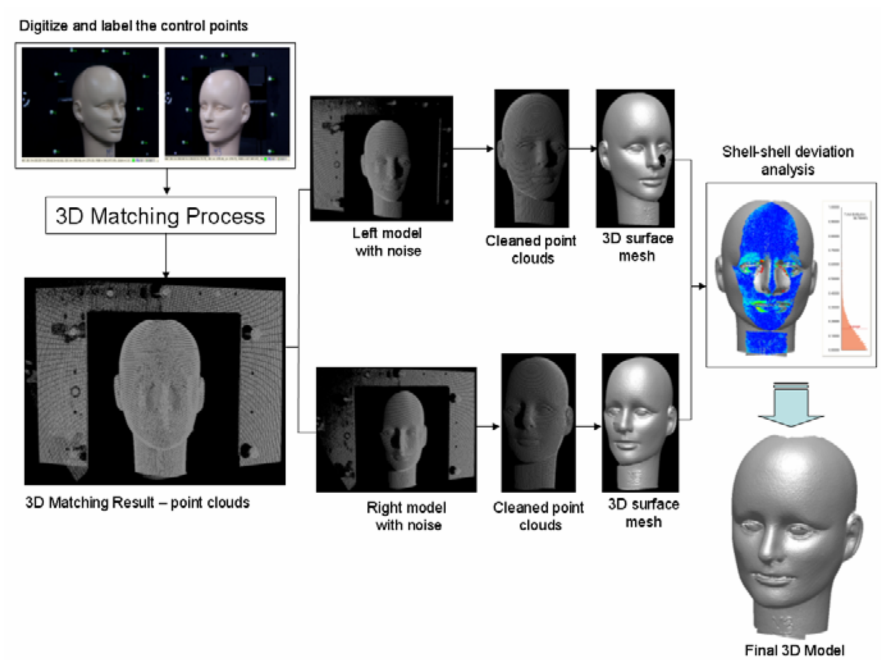


Figure 5.11: Pre-processing tasks for the development of final 3D model of craniofacial.

5.5 Summary

The chapter describes the method used in the integration of photogrammetry and laser scanning for the high accuracy alignment of craniofacial point clouds datasets. The existing IMetric software system is customized with the additional data processing tasks which includes the noise filtering, 3D surface development and shell-shell deviation analysis. The additional tasks is carried out using the RapidForm 2004 software.

CHAPTER 6

RESULTS AND ANALYSIS

6.1 Introduction

This chapter describes the results and the analysis of the results based on the tests that has been done in the study. The details of the results and the analysis are as given below:

6.2 Results

6.2.1 The Camera Calibration Results

Table 6.1 shows the camera calibration results of all the eight Sony F828 digital cameras. The results shows the average value calculated from five sets of calibration task per each camera.

Table 6.1: Camera calibration results - the lens parameters of eight Sony DSC F828 digital professional cameras

Parameters / *Camera ID*	c	x_p	y_p	k_1	k_2	k_3
Sony 01	7.3637	-0.0693	-0.0237	3.2E-03	-3.5E-05	-4.7E-07
Sony 02	7.3341	-0.0460	0.0009	3.2E-03	-3.2E-05	-4.3E-07
Sony 03	7.3403	-0.0376	-0.0111	3.2E-03	-3.2E-05	-4.1E-07
Sony 04	7.3121	-0.04603	-0.01165	3.3E-03	-3.1E-05	-4.5E-07
Sony 05	7.3129	-0.0142	-0.0480	3.2E-03	-2.3E-05	-7.1E-07
Sony 06	7.3384	-0.0589	0.0094	3.2E-03	-3.2E-05	-4.0E-07
Sony 07	7.3521	-0.0368	0.0005	3.1E-03	-2.5E-05	-6.1E-07
Sony 08	7.3402	-0.0284	-0.0395	3.2E-03	-3.1E-05	-4.9E-07

6.2.2 Stereophotogrammetric System Accuracy Test Results

The preliminary accuracy of the stereophotogrammetric measurements of both natural features and control frame methods is determined by the standard errors of the absolute orientation process in x, y and z coordinate axis. For both methods, the standard error of absolute orientation depends on the accuracy of three-dimensional ground control coordinates and the location of the control on the craniofacial surface. Table 6.2 shows the results of the optimum absolute orientation standard errors gained from both methods for the measurement of the mannequin (Figure 6.1). The accuracy of the system is then evaluated on real life human faces (as shown in Figure 6.2 and 6.3).

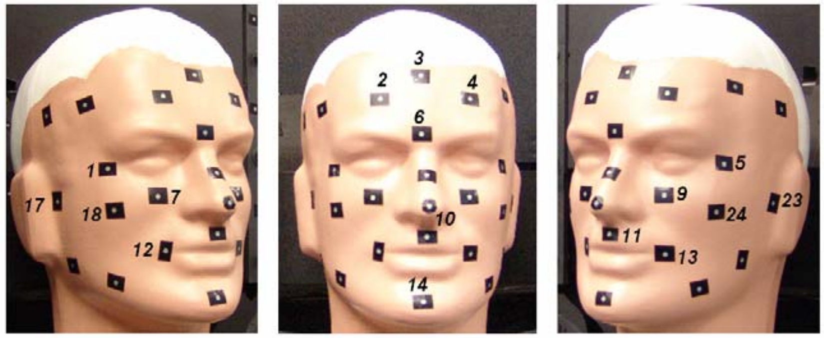


Figure 6.1: The mannequin used for the test. The results of the test are shown in Table 6.2, 6.3 and 6.4.

Table 6.2: Standard error of stereophotogrammetric absolute orientation

Methods	Absolute orientation standard errors in x, y and z axis (mm)
Control frame method	Front model (0.347, 0.303, 0.533) Left model (0.364, 0.225, 0.266) Right model (0.304, 0.222, 0.237)
Natural features method	Front model (0.063, 0.117, 0.246) Left model (0.125, 0.112, 0.310) Right model (0.216, 0.112, 0.320)

Table 6.3: Differences in slope distance between the test points

From point	To point	Caliper vs. bundle method (mm)	Natural point method vs. bundle method (mm)	Control frame method vs. bundle method (mm)
2	4	0.18	0.08	1.72
3	6	0.35	0.44	0.36
6	10	0.21	1.44	0.5
12	13	0.11	0.50	4.85
1	5	0.11	0.61	7.66
17	7	0.20	0.37	10.20
9	23	0.15	2.00	12.22
4	24	0.11	0.12	0.90
2	18	0.17	0.34	2.16
3	14	0.32	0.22	3.86
Statistics	**Mean**	***0.19***	***0.61***	***4.43***
	Variance	***0.01***	***0.38***	***18.07***
	Std Dev	***0.08***	***0.62***	***4.25***

Table 6.4: Differences in angle measurements between the selected test points

Three points involved (first – middle – last)	Natural point method vs. bundle method (deg)	Control frame method vs. bundle method (deg)
5-23-13	2.04	1.81
1-17-12	2.08	2.44
3-17-14	2.08	6.61
3-23-14	1.13	6.15
Mean	***1.83***	***4.25***
Variance	***0.16***	***4.60***
Std Dev	***0.40***	***2.14***

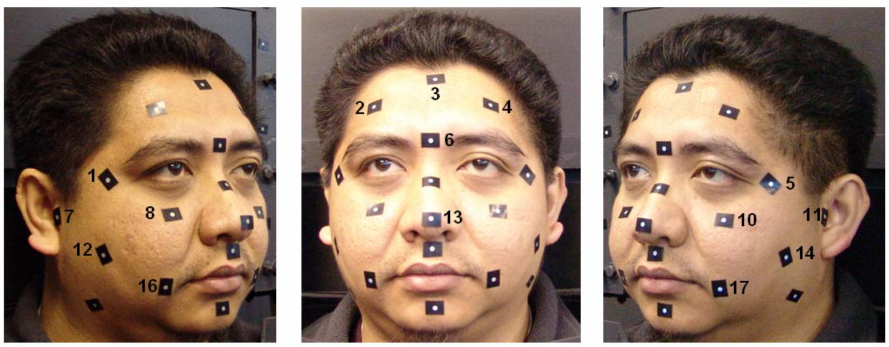


Figure 6.2: Real human face with signalized targets to represent the natural points and test points. The results of the test are shown in Table 6.5.

Table 6.5: The results of the test. Note that the distances calculated from the triangulation method are selected as “gold standard”.

From point	To point	Caliper vs. triangulation (mm)	Natural point method vs. triangulation (mm)	Control frame method vs. triangulation (mm)
2	4	0.11	1.36	3.57
3	6	0.03	0.77	1.61
6	13	0.56	2.01	1.87
16	17	1.60	0.20	0.81
1	5	0.30	0.70	7.64
7	8	0.66	2.00	1.67
10	11	0.63	0.66	2.87
4	14	1.09	1.10	3.56
2	12	0.31	0.15	1.44
Statistics	**Mean**	***0.59***	***0.99***	***2.78***
	Variance	***0.22***	***0.42***	***3.77***
	Std Dev	***0.50***	***0.65***	***1.94***

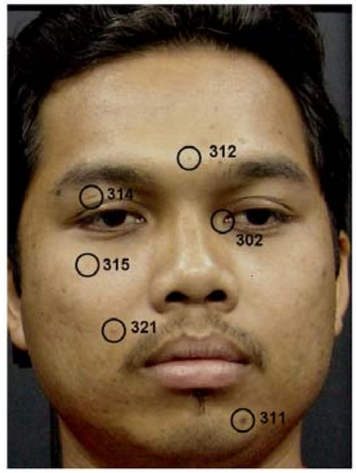


Figure 6.3: Real human face with natural selected natural features to be the test points. The results of the test are shown in Tables 6.6 and 6.7.

Table 6.6: The final evaluation test results – 3D Coordinates of the test points (selected natural features)

ID	***X (Bundle) (mm)***	***Y (Bundle) (mm)***	***Z (Bundle) (mm)***	***X (Natural Features) (mm)***	***Y (Natural Features) (mm)***	***Z (Natural Features) (mm)***	***X (Control Frame) (mm)***	***Y (Control Frame) (mm)***	***Z (Control Frame) (mm)***
302	494.987	441.666	135.194	494.915	441.630	135.041	496.668	441.330	123.338
311	503.696	350.880	142.704	503.782	350.316	143.927	505.572	347.963	130.074
312	477.479	469.187	150.929	478.318	469.434	149.722	478.954	469.753	136.810
314	432.230	452.385	138.444	432.199	452.540	138.132	431.738	452.267	124.461
315	431.687	421.251	139.741	431.735	421.890	140.836	431.837	421.257	124.461
321	442.932	391.326	145.140	442.787	391.572	145.086	443.514	389.738	131.196

Table 6.7: The final evaluation test results - analysis of the coordinate's differences between natural features technique, control frame technique and bundle adjustment

ID	***X (Natural Features-Bundle) (mm)***	***Y (Natural Features-Bundle) (mm)***	***Z (Natural Features-Bundle) (mm)***	***X (Control Frame-Bundle) (mm)***	***Y (Control Frame-Bundle) (mm)***	***Z (Control Frame-Bundle) (mm)***
302	-0.072	-0.036	-0.153	1.680	-0.336	-11.856
311	0.085	-0.564	1.222	1.875	-2.917	-12.630
312	0.838	0.246	-1.207	1.474	0.565	-14.119
314	-0.031	0.154	-0.312	-0.492	-0.118	-13.983
315	0.047	0.638	1.094	0.149	0.005	-15.280
321	-0.145	0.245	-0.054	0.581	-1.588	-13.944
Mean	***0.120***	***0.113***	***0.098***	***0.878***	***-0.731***	***-13.635***
Std Dev	***0.330***	***0.363***	***0.838***	***0.865***	***1.173***	***1.105***
Variance	***0.108***	***0.132***	***0.702***	***0.748***	***1.377***	***1.222***
RMSE	***0.351***	***0.381***	***0.843***	***1.232***	***1.383***	***13.680***

6.2.3 Results of the Camera Synchronization Test

The camera synchronization test is successfully carried out as planned in methodology, by using a plumb line method. The test point P2 is used as an evaluated mark for the test. Table 6.8 shows the results.

Table 6.8: The stereocamera synchronization evaluation results on test point P2

Observation Pairs	Triangulation Accuracy (mm)	dx (mm)	dy (mm)	dz (mm)
C6 – C1	1.932	-0.949	-1.096	0.800
C6 – C2	1.826	-0.710	-0.948	0.345
C6 – C3	2.087	-0.970	-0.216	0.925
C6 – C4	2.678	-1.452	-0.171	1.103
C6 – C5	*0.591*	*reference*	*reference*	*reference*
C6 – C7	1.501	-0.581	-0.367	0.047
C6 – C8	1.374	-0.399	-0.451	0.273
	Mean (mm)	-0.844	-0.542	0.582
	Std Dev. (mm)	0.369	0.388	0.418

The results show that the accuracy of the synchronization device is below the 0.7mm. Therefore it satisfies the craniofacial mapping accuracy.

6.2.4 Laser Scanner Calibration Results

As mentioned in Chapter 4 (System Calibration), the laser scanner is calibrated using three calibrated objects, the cylinder, dental cast and mannequin. Below are the results of the calibration which are related to the test objects.

6.2.4.1. The Cylindrical Object

The computed difference and standard deviation based on five sets of measurement are provided in Table 6.9. The standard deviation is within the limit of 0.7 mm as required by our medical mapping project.

Table 6.9: Measured and true dimension of the cylinder

Dimension	Averaged dimension (mm)	True dimension (mm)	Difference (mm)	Standard Deviation (mm)
Height	196.591	196.174	*0.366*	0.191
Width	120.325	120.836	*0.511*	0.203

6.2.4.2. The Dental Cast

Table 6.10: Slope distance comparison between three measurement techniques

Slope Distance	Scanner (mm) (A)	Photogrammetry (mm) (B)	Microscribe (mm) (C)	A-B (mm)	A-C (mm)
5-6	20.769	20.552	20.510	0.217	0.259
5-1	60.793	60.637	60.601	0.156	0.192
5-2	49.503	49.484	49.585	0.019	-0.082
5-3	42.919	42.865	42.929	0.054	-0.010
4-3	38.261	38.399	38.414	-0.138	-0.153
6-1	60.128	59.637	59.680	0.491	0.448
6-2	56.903	56.653	56.798	0.250	0.105
6-3	55.805	55.715	55.938	0.090	-0.133
2-3	17.161	17.257	17.102	-0.096	0.059
1-1	24.353	24.140	24.124	0.213	0.229
			Mean	***0.172***	***0.167***
			Std Dev.	***0.128***	***0.119***

The results of dental cast study show that there are no significance differences statistically between the three measurements (Table 6.10). All three techniques satisfied our project accuracy of requirement 0.7 mm at one standard deviation. However, the scanner is a very efficient method of capturing the 3D surface of the dental cast.

6.2.4.3. The Mannequin

The results of the study on mannequins show that the differences and standard deviations were also within the limit required for our medical project (Table 6.11). In this case, measurements obtained by the photogrammetric technique are held as the true values.

Table 6.11: Slope distance comparison between photogrammetry and scanner

Slope distance	Photogrammetry (mm) (A)	Scanner (mm) (B)	A-B (mm)
3-5	51.010	50.817	0.193
4-6	64.009	64.122	-0.113
3-7	105.197	105.464	-0.267
5-7	105.366	105.613	-0.247
3-2	83.003	83.079	-0.076
5-9	88.703	88.750	-0.047
		Mean	-0.093
		Std. Dev	0.166

6.2.5 The Results of the Critical Factors for Craniofacial Mapping using Laser Scanner

6.2.5.1. Optimal Scan Distance and Camera Focal Length

The slope distances between selected landmarks are determined by Microscribe 3D digitizer system (Immersion Corporation, San Jose, CA) and the average of five sets is used as the 'true' slope distance (Figure 6.4). The same slope distances measured on the 3D craniofacial surface model are compared with the 'true value'.

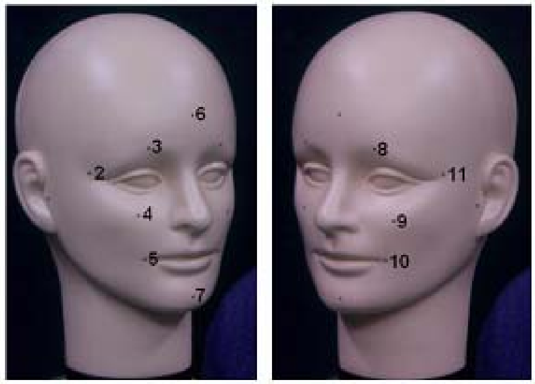


Figure 6.4: The location of the anthropometric marks on the mannequin

Table 6.12 and Table 6.13 show the results of the middle-angle lens and wide-angle lens tests respectively. The scan distances (S_d in mm) are shown at the top of the tables and all measurements are in millimetres.

Table 6.12: Slope distance comparison of the middle-angle lens measurement of various scan distances

From -To	**S_d = 700**	**S_d = 800**	**S_d = 900**	**S_d = 1000**
3-8	-0·063	-0·011	0·642	0·514
4-9	-0·249	0·825	0·978	0·83
5-10	-0·084	-0·309	1·186	0·238
6-7	0·112	0·709	1·57	0·904
3-4	-0·019	0·64	0·422	0·283
8-9	-0·12	0·569	0·677	0·411
2-11	-0·388	0·548	2·205	2·193
Mean	-0·116	0·424	1·097	0·768
Std Dev	0·162	0·419	0·621	0·678
RMSE	0·189	0·575	1·239	0·992

Table 6.13: Slope distance comparison of the Wide-angle lens measurement of various scan distances

From - To	**S_d = 700**	**S_d = 800**	**S_d = 900**	**S_d = 1000**
3-8	1·632	1·554	0·871	1·082
4-9	2·501	1·645	1·613	1·541
5-10	2·076	1·618	1·458	1·027
6-7	4·075	3·64	2·948	3·042
3-4	2·115	1·629	1·687	1·695
8-9	1·6	0·995	1·537	1·54
2-11	4·116	3·854	3·716	2·44
Mean	2·588	2·134	1·976	1·767
Std Dev	1·075	1·127	0·989	0·731
RMSE	2·773	2·375	2·178	1·892

The results show that the middle-angle lens gives the best values for all scan distances tested. However, the results also show that the accuracy reduces as the scanned distance increases.

6.2.5.2. Laser Intensity

Figure 6.5 shows: (a) the surface of mannequin darkens as the beam intensity increases; (b) the real shape and shade of the eye-area; and (c) the shade of shadow of the eye-area increase as the intensity increases. Figure 6.6 shows that the scan error versus the beam intensity. As can be seen in Figures 6.5 and 6.6, an increase in Laser intensity value causes adverse effects on the recorded texture and spatial accuracy of the modelled surface. Minolta VI-910 3D laser scanner is an intelligent scanner; a built-in sensor determines the optimal laser intensity required at a set scan distance. Figure 6.7 shows the error in the shell/shell deviation between a surface model scanned at the optimal laser intensity (around 20 to 40) and one scanned at intensity of 150. Figure 6.8 shows the average shell/shell deviation error versus the Laser intensity. In addition, Table 6.14 shows that the standard deviation of the slope distance difference is smallest at I = 20 and the value increases steadily as the intensity value increases from I = 20 to I = 150. The size of the measurement error is acceptable for the project at I = 80.

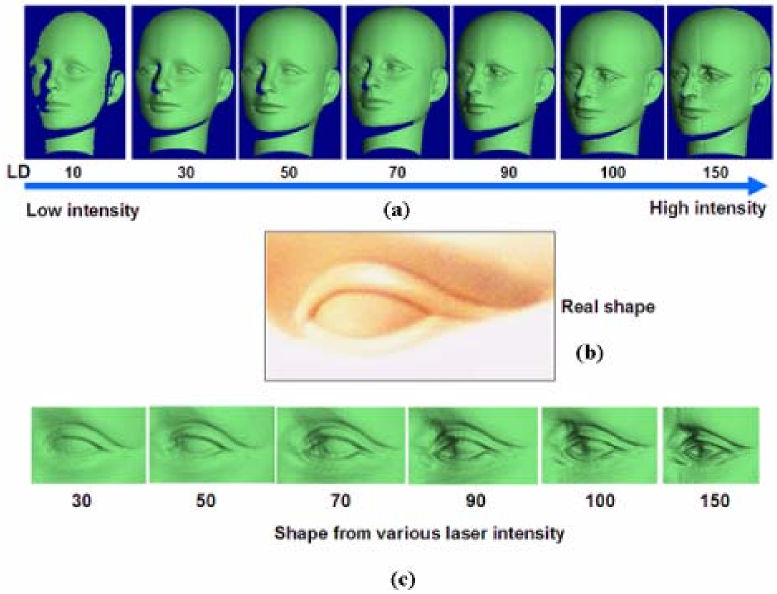


Figure 6.5: Texture quality vs laser beam intensity. Note the shade of the shadow as the beam intensity increases

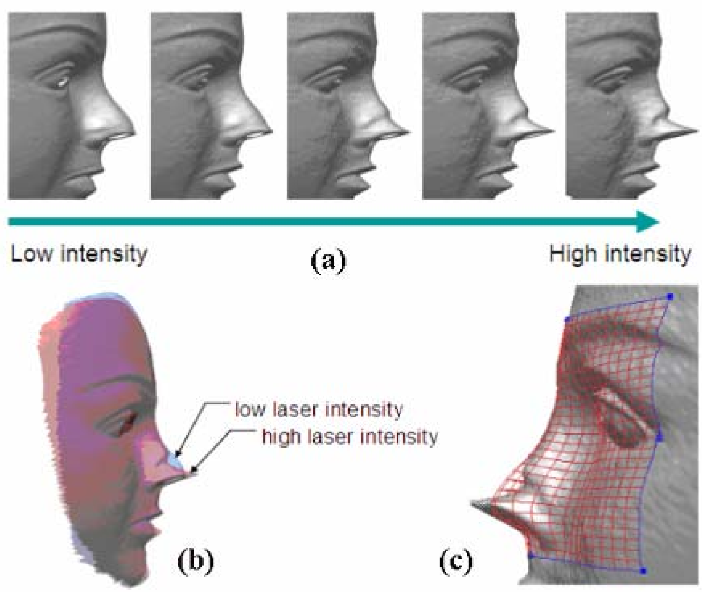


Figure 6.6: Scan error vs. beam intensity: (a) shape change based intensity; (b) surface error; and (c) TIN error

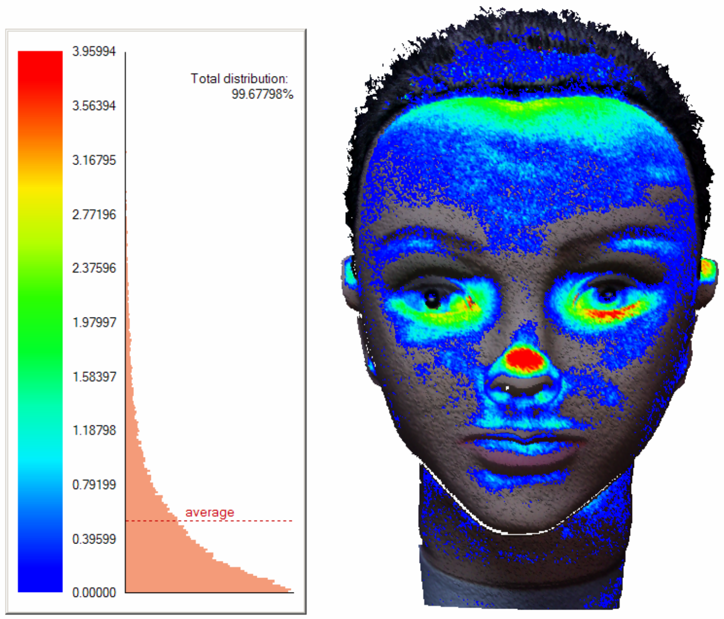


Figure 6.7: Shell/shell deviation analysis. In the colour chart, red colour (top) represents the maximum deviation value

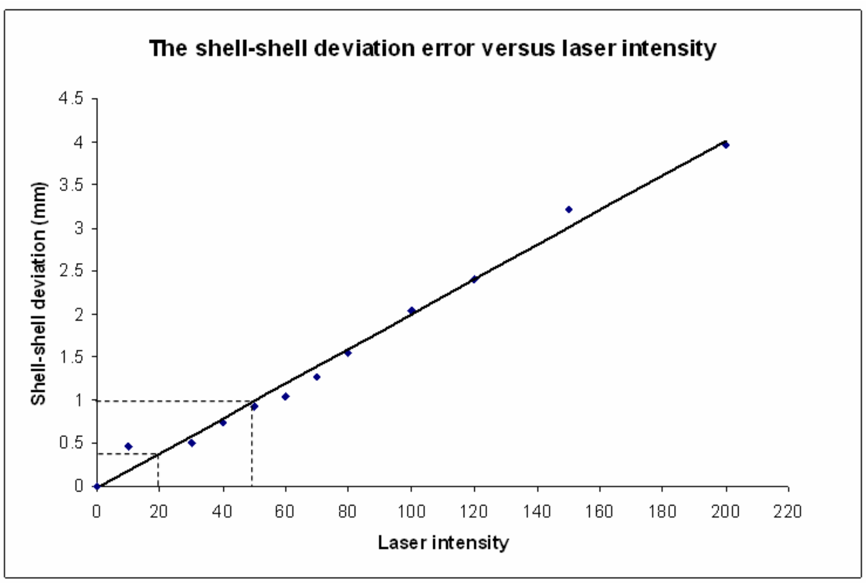


Figure 6.8: A graph showing the averaged shell/shell deviation error versus the Laser intensity value. Note that the optimal intensity lies between the dotted lines

Table 6.14: Slope distance comparison of the beam intensity test

From - To	At I=20 (mm)	At I=50 (mm)	At I=80 (mm)	At I=100 (mm)	At I=120 (mm)	At I=150 (mm)
3-8	-0·202	0·357	0·377	-0·327	-0·34	-0·341
4-9	0·056	0·503	0·541	0·239	0·297	-0·459
5-10	0·005	0·349	0·33	0·279	-0·275	-0·246
6-7	0·552	0·721	1·207	2·301	2·377	2·406
3-4	-0·09	-0·528	1·183	-1·216	1·.219	1·247
8-9	-0·012	0·14	-0·177	0·191	-0·433	0·871
2-11	0·589	0·768	0·957	1·025	1·015	1.003
Mean	0·128	0·33	0·682	0·703	0·753	0·64
Std dev	0·313	0·437	0·427	0·879	0·88	1·051

6.2.5.3. Scanning Resolution

The shell/shell deviation analysis is carried out to find the maximum deviation value between (a) low – high resolutions datasets and (b) medium – high resolutions datasets. The results of the study are presented in Table 6.15.

Table 6.15: Shell/shell deviation analysis of scanning resolution

Resolution Test	Maximum Deviation (mm)	Average Deviation (mm)	Standard Deviation (mm)
Low-High	1·065	0·446	0·215
Medium-High	0·349	0·040	0·047

Table 6.15 shows that the optimal scanning resolution suitable for craniofacial surface is the medium resolution with maximum shell/shell deviation of 0.349mm as compared to low resolution of 1.065. The test results also show that both high and medium resolution scans were 576 per square inch (0.044 mm/pixel) and the low resolution is only 144 per square inch. Figure 6.9 shows the distribution of points in the point cloud. Table 6.16 shows the results of slope distance comparison and the RMSEs indicates that both medium and high resolution scans are suitable for our project.

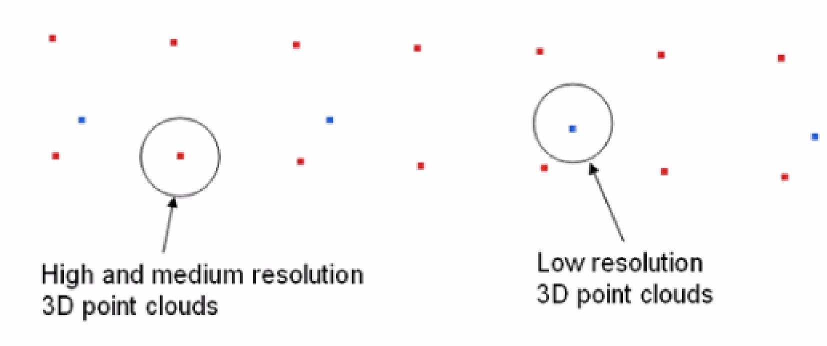


Figure 6.9: Point-cloud density based on scanning resolution

Table 6.16: Slope distance comparison of the scanning resolution test

From -To	Low Resolution (mm)	Medium Resolution (mm)	High Resolution (mm)
3-8	-0·553	-0·727	-0·515
4-9	-0·052	-0·104	0·168
5-10	-0·322	-0·586	-0·658
6-7	2·318	0·168	-0·176
3-4	1·195	0·464	0·767
8-9	1·023	0·261	0·692
2-11	0·444	0·731	0·973
Mean	0·579	0·03	0·179
Std Dev	0·934	0·496	0·603
RMSE	1·099	0·497	0·629

6.2.5.4. Number of Overlapping Scan for the Craniofacial Area

Figure 6.10 shows the registration and merging technique carried out to build a complete 3D surface of the craniofacial area using three overlapping scans. The results of the slope distance comparison between the ‘true’, 2-scan and 3-scan configuration shows that the best measurement belongs to the 3-scan configuration (Table 6.17). However, the two-scan configuration gives an RMSE of 0.632mm which satisfies the landmark measurement accuracy required for our craniofacial project. By and large, a 3-scan configuration requires the use of three scanners and more time scanning; and that would be a more expensive exercise.

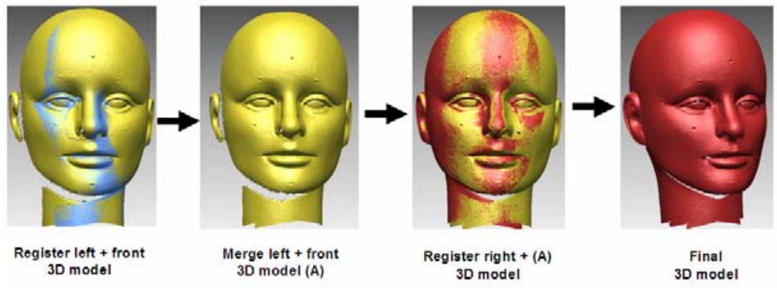


Figure 6.10: Registration of a three-scan craniofacial mapping

Table 6.17: Slope distance comparison between the ‘true’ value, 2-scan and 3-scan measurement.

From-To	**True value (mm) (A)**	**2 scans test (mm) (B)**	**3 scans test (mm) (C)**	**B-A**	**C-A**
3-8	52·959	52·867	52·939	-0·092	-0·02
4-9	61·387	61·040	61·551	-0·347	0·164
5-10	57·745	57·150	57·672	-0·595	-0·073
6-7	115·239	115·826	115·577	0·587	0·338
3-4	46·573	47·192	47·196	0·619	0·623
8-9	47·705	48·202	48·143	0·497	0·438
2-11	112·505	113·547	113·483	1·042	0·978
			Mean	0·244	0·349
			Std Dev	0·551	0·344
			RMSE	0·603	0·49

6.2.5.5. Scan Angle

In the data analysis, slope distances between landmarks in the data analysis are compared with the ‘true’ value. In addition, the registration accuracy of each scan angle is evaluated using shell-to-shell deviation method.

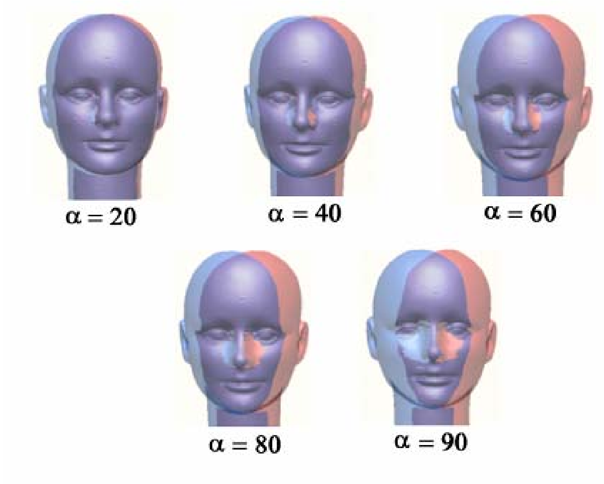


Figure 6.11: The effect of scan angle on the corresponding overlapping area

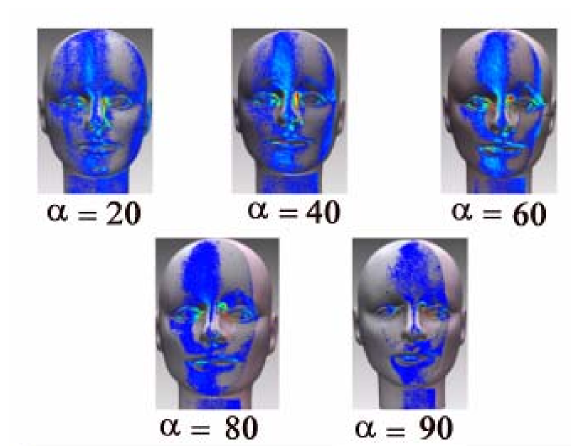


Figure 6.12: Shell/Shell deviation analysis of the scan angle test

Figure 6.11 shows the size of the overlapping area in relationship to the scanned angle. Figure 6.12 shows that the shell/shell deviation error at 90° scan angle is smaller as compared to other scan angles. The test also involves larger scan angles (i.e. 120° and 140°). However, the registration fails (Figure 6.13) because of the limited number of available corresponding features to perform high quality registration (Figure 6.14).

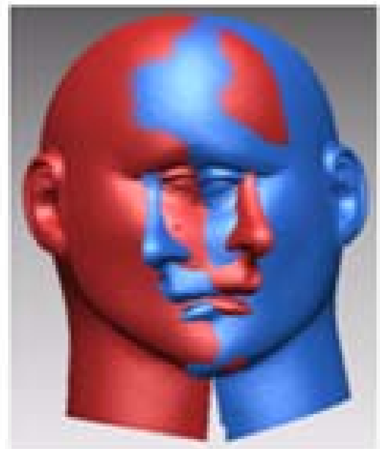


Figure 6.13: Errors in the registration of the left and right scans of 120° scan angle.

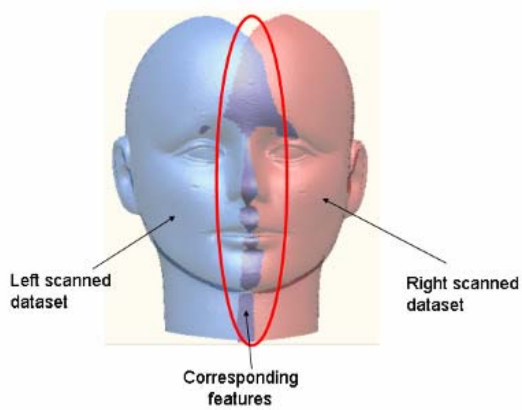


Figure 6.14: Limited number of corresponding features to perform accurate 3D registration of the two overlapping scans.

The test on the optimal scan angle is evaluated by analysing completeness of the 3D model that covers the craniofacial area (from left ear to right ear, from the hair line to the bottom of the chin). Figure 6.15 shows the effect of the scanning angle on the shape of the modelled mannequin's ear. Table 6.18 shows the results of the slope distance comparison of the scan angle test. The RMSEs of scanned angle 60°, 80° and 90° satisfy the project accuracy requirement.

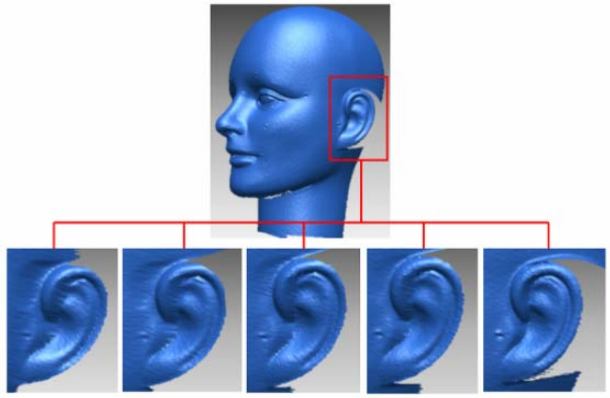


Figure 6.15: Effect of the scan angle to the modelled ear.

Table 6.18: Slope distance comparison of the scan angle test. Note that only the differences are presented

From -To	α = 20 ° (mm)	α = 40 ° (mm)	α = 60 ° (mm)	α = 80° (mm)	α = 90 ° (mm)	α = 120 ° (mm)
3-8	-0·645	-0·747	-0·724	-0·532	-0·542	-0·297
4-9	-0·042	-0·474	0·107	0	-0·436	0·13
5-10	-0·431	-0·233	-0·636	0·251	0·619	-0·365
6-7	-0·82	-0·138	-0·384	-0·556	-0·017	-1·97
3-4	-0·035	-0·592	-0·472	-0·177	-0·197	-0·339
8-9	-0·571	-0·602	-0·213	-0·058	0·406	-0·024
2-11	-1·381	-1·361	-1·033	-1·433	-1·411	-1·514
Mean	-0·561	-0·592	-0·387	-0·358	-0·225	-0·626
s/d	0·433	0·371	0·276	0·514	0·621	0·736
RMSE	0·708	0·699	0·588	0·626	0·661	0·966

6.2.6 The Results on the Integration Tests

The results on the integration of photogrammetry and laser scanner system in modelling craniofacial 3D surface model are shown in Tables 6.19, 6.20 and 6.21. The results are based on reliability test of the 3D point cloud alignment technique by using photogrammetric targets.

Table 6.19: Reliability test results of the proposed 3D alignment technique – test on mannequin 1

Test on Mannequin 1	**Left Model Matching Accuracy (mm)**	**Right Model Matching Accuracy (mm)**	**Average Distances (mm)**	**Standard Deviation (mm)**
Test 1	Vx = 0.535 Vy = 0.378 Vz = 0.223	Vx = 0.295 Vy = 0.214 Vz = 0.182	0.285	0.741
Test 2	Vx = 0.536 Vy = 0.379 Vz = 0.237	Vx = 0.304 Vy = 0.220 Vz = 0.191	0.251	0.624
Test 3	Vx = 0.536 Vy = 0.378 Vz = 0.238	Vx = 0.303 Vy = 0.218 Vz = 0.189	0.271	0.660
Test 4	Vx = 0.543 Vy = 0.382 Vz = 0.253	Vx = 0.322 Vy = 0.194 Vz = 0.131	0.267	0.701
Test 5	Vx = 0.530 Vy = 0.377 Vz = 0.230	Vx = 0.296 Vy = 0.214 Vz = 0.185	0.272	0.693

Table 6.20: Reliability test results of the proposed 3D alignment technique – test on mannequin 2

Test on Mannequin 2	**Left Model Matching Accuracy (mm)**	**Right Model Matching Accuracy (mm)**	**Average Distances (mm)**	**Standard Deviation (mm)**
Test 1	Vx = 0.535 Vy = 0.376 Vz = 0.244	Vx = 0.316 Vy = 0.222 Vz = 0.195	0.261	0.637
Test 2	Vx = 0.531 Vy = 0.375 Vz = 0.238	Vx = 0.305 Vy = 0.217 Vz = 0.196	0.209	0.478
Test 3	Vx = 0.526 Vy = 0.370 Vz = 0.247	Vx = 0.313 Vy = 0.226 Vz = 0.191	0.221	0.482
Test 4	Vx = 0.530 Vy = 0.375 Vz = 0.238	Vx = 0.299 Vy = 0.212 Vz = 0.196	0.274	0.673
Test 5	Vx = 0.532 Vy = 0.373 Vz = 0.238	Vx = 0.304 Vy = 0.227 Vz = 0.166	0.234	0.538

Table 6.21: Reliability test results of the proposed 3D alignment technique – test on mannequin 3

Test on Mannequin 3	**Left Model Matching Accuracy (mm)**	**Right Model Matching Accuracy (mm)**	**Average Distances (mm)**	**Standard Deviation (mm)**
Test 1	Vx = 0.438 Vy = 0.310 Vz = 0.256	Vx = 0.325 Vy = 0.144 Vz = 0.141	0.129	0.216
Test 2	Vx = 0.438 Vy = 0.306 Vz = 0.259	Vx = 0.240 Vy = 0.143 Vz = 0.134	0.137	0.248
Test 3	Vx = 0.434 Vy = 0.306 Vz = 0.252	Vx = 0.237 Vy = 0.140 Vz = 0.138	0.241	0.615
Test 4	Vx = 0.434 Vy = 0.304 Vz = 0.277	Vx = 0.237 Vy = 0.144 Vz = 0.145	0.236	0.604
Test 5	Vx = 0.433 Vy = 0.300 Vz = 0.284	Vx = 0.238 Vy = 0.144 Vz = 0.143	0.200	0.440

6.3 Advanced Statistical Analysis

The advanced statistical test is carried out to analyse the results of the study, statistically. There are two three types of advanced statistical analysis that have been applied in this study, as given below:

a. F-variance ratio test
b. Analysis of Variance test (ANOVA)
c. t-test for significance of camera calibration parameters

a. F variance ratio test

The analysis is carried out using the one-tailed F-Test for two sample variances statistical test. The confidence level for the test was 95% (where $\alpha = 0.05$). The hyporesearch of the test is:

$$H_0 : \sigma_1 = \sigma_2 \qquad H_A : \sigma_1 \neq \sigma_2 \tag{6.1}$$

The F-Test is carried out using the formula:

$$F = \frac{S_1^2}{S_2^2} \tag{6.2}$$

Where S_1^2 refers to the variance of sample 1 and S_2^2 refers to the variance of sample 2. The null hyporesearch will be rejected if the calculated F value (equation 6.2) is higher than the critical F value (predicted from the F-distribution table) with selected level of significance (e.g. $\alpha = 0.05$). The rejection of H_o shows that the test parameters (from two samples) is not equal. In this study, the F variance ratio test is used to analyse the significance of some of the results, for example to analyse that there are significance different between the natural features method and the control frame method in the measurement of craniofacial landmarks.

b. Analysis of Variance Test (ANOVA)

In this study, the one-way between groups ANOVA is used to analyse the variation between the populations mean for the groups. The statistical test is carried out using the F-mean square ratio test between the samples in groups. The obtained value of the F test statistic is found by applying the formula below:

$$F = \frac{MS_{between}}{MS_{within}} \tag{6.3}$$

The hyporesearch of the test is:

$$H_0 : \mu_1 = \mu_2 = \mu_3 = ...\mu_i$$
$$H_A : \mu_1 \neq \mu_2 \neq \mu_3 \neq ....\mu_i \tag{6.4}$$

Where $\mu_1, \mu_2, ...\mu_i$ refers to populations mean for the groups. The null hyporesearch will be rejected if the calculated F value (equation 6.3) is higher than the critical F value (predicted from the F-distribution table) with selected level of significance (e.g. $\alpha = 0.05$). The rejection of H_o shows that the test parameters is not equal. In this study, the F variance ratio test is used to analyse the significance of some of the results, for example to analyse that there are significance variation in the focal length of the camera.

c. t-test for Significance of Camera Calibration Parameters

The analysis is carried out using the statistical t-test. The confidence level for the test is 95% (where $\alpha = 0.05$) and 99% (where $\alpha = 0.01$). The hyporesearch of the test is:

$$H_0 : \beta = 0$$
$$H_A : \beta \rangle 0 \tag{6.5}$$

The t-test is carried out using the formula:

$$t = \frac{\beta}{S_\beta} \tag{6.6}$$

Where,

$\beta = f, x_p, y_p, K_1, K_2, K_3, P_1, P_2, B_1, B_2$ (camera calibration prameters)

$S_\beta =$ standard error of the calibration parameters

The null hyporesearch (which is stated that the tested parameters are not significance) will be rejected if the calculated t value (equation 6.4) is higher than the critical t value (predicted from the t-distribution table) with selected level of significance (e.g. $\alpha = 0.05$). With the rejected of H_o, the test parameters is statistically significance (accept H_A).

6.3.1 The Statistical Analysis of Camera Calibration Results

The statistical analysis of the camera calibration results are carried out using the Analysis of Variance (ANOVA) method. The analysis is focused on the focal length of the cameras in order to study the effect of the variation of that parameter for craniofacial mapping. Table 6.22 shows the ANOVA results.

Table 6.22: ANOVA results on the test of the focal length of the eight cameras

Groups	*Count*	*Sum*	*Average*	*Variance*
Camera 1	3	22.091	7.363667	1.056E-05
Camera 2	3	22.0022	7.334067	1.033E-07
Camera 3	3	22.0209	7.3403	4E-08
Camera 4	3	21.9364	7.312133	1.773E-06
Camera 5	3	21.9387	7.3129	3.6E-07
Camera 6	3	22.0151	7.338367	1.433E-07
Camera 7	3	22.0563	7.3521	1.11E-06
Camera 8	3	22.0208	7.340267	3.333E-07

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.00650913	7	0.00093	***515.64286***	1.265E-17	***2.657197***
Within Groups	2.8853E-05	16	1.8E-06			
Total	0.00653799	23				

The results show that there is a significance difference between the focal length of the cameras. The calculated value for F (515.643) exceeds the critical value of F (2.657) with high significance different (with very small p-value). The test shows that the variation of the camera focal length is an important factor in craniofacial stereophotogrammetric mapping.

The ANOVA method is also used to study the effect of the focal length (of the eight cameras) if a new camera (with different brand and focal length) is introduced in the stereophotogrammetric imaging system. The results of the test are shown in Table 6.23.

Table 6.23: ANOVA results on the test of the focal length of the eight cameras and the effect of additional camera in craniofacial mapping

Groups	*Count*	*Sum*	*Average*	*Variance*
Camera 1	3	22.091	7.363667	1.056E-05
Camera 2	3	22.0022	7.334067	1.033E-07
Camera 3	3	22.0209	7.3403	4E-08
Camera 4	3	21.9364	7.312133	1.773E-06
Camera 5	3	21.9387	7.3129	3.6E-07
Camera 6	3	22.0151	7.338367	1.433E-07
Camera 7	3	22.0563	7.3521	1.11E-06
Camera 8	3	22.0208	7.340267	3.333E-07
Camera 9 (additional)	*3*	*24.595*	*8.198333*	*0.0001083*

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1.98615959	8	0.24827	***18201.609***	1.481E-33	***2.510158***
Within Groups	0.00024552	18	1.36E-05			
Total	1.98640511	26				

The results also show that there is a high significance difference between the focal length of the eight cameras and the additional camera. The calculated value for F (18201.609) exceeds the critical value of F (2.510) with high significance difference (with very small p-value). The test also shows that the additional camera will give big impact on the accuracy of craniofacial stereophotogrammetric mapping.

6.3.2 Test of Significance of the Camera Calibration Parameters

The test of significance of the camera calibration parameters is carried out using the first calibration task as a test data. The results of the test are shown in Tables 6.24, 6.25, 6.26, 6.27, 6.28, 6.29, 6.30 and 6.31 for the Sony Camera 1, Sony

Camera 2, Sony Camera 3, Sony Camera 4, Sony Camera 5, Sony Camera 6, Sony Camera 7 and Sony Camera 8, respectively.

Table 6.24: The Significance test for Sony Camera 1

	SIGNIFICANCE TEST FOR CAMERA CALIBRATION PARAMETERS				
	CAMERA #		*1*		
	DEGREE OF FREEDOM		1224		
	CRITICAL VALUE FOR t (95% CL)		1.645		
	CRITICAL VALUE FOR t (99% CL)		2.326		
	PARAMETERS	***STD ERROR***	***CAL t***	***95% CL***	***99% CL***
f	7.3637	0.0009582	7684.93	*YES*	*YES*
Xp	0.0693	0.0005826	118.9495	*YES*	*YES*
Yp	0.0237	0.0008988	26.36849	*YES*	*YES*
K1	0.00316259	0.000009609	329.1279	*YES*	*YES*
K2	0.000035119	9.859E-07	35.62126	*YES*	*YES*
K3	4.78528E-07	2.957E-08	16.18289	*YES*	*YES*
P1	4.18338E-05	0.000003662	11.42376	*YES*	*YES*
P2	0.00007123	0.000002904	24.52824	*YES*	*YES*
B1	0.000417706	0.0000328	12.73494	*YES*	*YES*
B2	0.000126418	0.00002823	4.478144	*YES*	*YES*
	Note: YES - SIGNIFICANCE, NO - NOT SIGNIFICANCE				

Table 6.25: The Significance test for Sony Camera 2

	SIGNIFICANCE TEST FOR CAMERA CALIBRATION PARAMETERS				
	CAMERA #		2		
	DEGREE OF FREEDOM		1222		
	CRITICAL VALUE FOR t (95% CL)		1.645		
	CRITICAL VALUE FOR t (99% CL)		2.326		
	PARAMETERS	***STD ERROR***	***CAL t***	***95% CL***	***99% CL***
f	7.3342	0.001061	*6912.535*	*YES*	*YES*
Xp	0.046	0.0006433	*71.5063*	*YES*	*YES*
Yp	0.0009	0.0009834	*0.915192*	*NO*	*NO*
K1	0.00320174	0.00001095	*292.3963*	*YES*	*YES*
K2	3.20887E-05	0.000001148	27.95183	*YES*	*YES*
K3	4.27595E-07	3.536E-08	12.09262	*YES*	*YES*
P1	2.16417E-05	0.000004082	5.301739	*YES*	*YES*
P2	4.83701E-05	0.000003177	15.22509	*YES*	*YES*
B1	0.000217694	0.00003602	6.043698	*YES*	*YES*
B2	0.000311964	0.00003105	10.04715	*YES*	*YES*
	Note: YES - SIGNIFICANCE, NO - NOT SIGNIFICANCE				

Table 6.26: The Significance test for Sony Camera 3

SIGNIFICANCE TEST FOR CAMERA CALIBRATION PARAMETERS

CAMERA #	3
DEGREE OF FREEDOM	1228
CRITICAL VALUE FOR t (95% CL)	1.645
CRITICAL VALUE FOR t (99% CL)	2.326

	PARAMETERS	***STD ERROR***	***CAL t***	***95% CL***	***99% CL***
f	7.3405	0.0009938	*7386.295*	YES	YES
Xp	0.0376	0.000602	*62.45847*	YES	YES
Yp	0.0111	0.0009217	*12.04296*	YES	YES
K1	0.0032254	0.00001026	*314.3665*	YES	YES
K2	3.21032E-05	0.000001076	29.83569	YES	YES
K3	4.09869E-07	3.307E-08	12.39398	YES	YES
P1	0.000126627	0.000003812	33.218	YES	YES
P2	6.10026E-05	0.000002993	20.38176	YES	YES
B1	0.00034867	0.00003377	10.32484	YES	YES
B2	0.000103159	0.00002915	3.538902	YES	YES

Note: YES - SIGNIFICANCE, NO - NOT SIGNIFICANCE

Table 6.27: The Significance test for Sony Camera 4

SIGNIFICANCE TEST FOR CAMERA CALIBRATION PARAMETERS

CAMERA #	4
DEGREE OF FREEDOM	1226
CRITICAL VALUE FOR t (95% CL)	1.645
CRITICAL VALUE FOR t (99% CL)	2.326

	PARAMETERS	***STD ERROR***	***CAL t***	***95% CL***	***99% CL***
f	7.313	0.0008526	8577.293	*YES*	*YES*
Xp	0.046	0.0005166	89.04375	*YES*	*YES*
Yp	0.0117	0.0007951	14.71513	*YES*	*YES*
K1	0.00330238	0.000009003	366.8088	*YES*	*YES*
K2	3.14625E-05	9.491E-07	33.14983	*YES*	*YES*
K3	4.45008E-07	2.919E-08	15.24522	*YES*	*YES*
P1	9.85715E-06	0.00000331	2.977991	*YES*	*YES*
P2	0.000064262	0.000002651	24.24066	*YES*	*YES*
B1	0.000442958	0.00002924	15.14904	*YES*	*YES*
B2	0.000215681	0.00002526	8.53844	*YES*	*YES*

Note: YES - SIGNIFICANCE, NO - NOT SIGNIFICANCE

Table 6.28: The Significance test for Sony Camera 5

SIGNIFICANCE TEST FOR CAMERA CALIBRATION PARAMETERS

CAMERA #	5
DEGREE OF FREEDOM	1222
CRITICAL VALUE FOR t (95% CL)	1.645
CRITICAL VALUE FOR t (99% CL)	2.326

	PARAMETERS	***STD ERROR***	***CAL t***	***95% CL***	***99% CL***
f	7.3135	0.0008388	*8719.003*	*YES*	*YES*
Xp	0.0142	0.0005104	*27.82132*	*YES*	*YES*
Yp	0.048	0.0007834	*61.27138*	*YES*	*YES*
K1	0.00323216	0.000008643	*373.9627*	*YES*	*YES*
K2	0.000022877	8.974E-07	25.49253	*YES*	*YES*
K3	7.06022E-07	2.711E-08	26.04286	*YES*	*YES*
P1	2.67854E-05	0.000003272	8.186247	*YES*	*YES*
P2	2.32449E-05	0.000002653	8.761741	*YES*	*YES*
B1	0.000393982	0.00002889	13.63731	*YES*	*YES*
B2	0.000166767	0.00002501	6.668013	*YES*	*YES*

Note: YES - SIGNIFICANCE, NO - NOT SIGNIFICANCE

Table 6.29: The Significance test for Sony Camera 6

SIGNIFICANCE TEST FOR CAMERA CALIBRATION PARAMETERS

CAMERA #	6
DEGREE OF FREEDOM	1210
CRITICAL VALUE FOR t (95% CL)	1.645
CRITICAL VALUE FOR t (99% CL)	2.326

	PARAMETERS	***STD ERROR***	***CAL t***	***95% CL***	***99% CL***
f	7.3388	0.0009094	8069.936	*YES*	*YES*
Xp	0.0589	0.0005577	105.6123	*YES*	*YES*
Yp	0.0094	0.000868	10.82949	*YES*	*YES*
K1	0.0032264	0.00000963	335.0363	*YES*	*YES*
K2	3.21983E-05	9.981E-07	32.25959	*YES*	*YES*
K3	3.9615E-07	2.979E-08	13.29809	*YES*	*YES*
P1	7.12965E-06	0.000003549	2.008918	*YES*	*NO*
P2	0.000177587	0.000002911	61.0055	*YES*	*YES*
B1	0.00032503	0.00003166	10.26627	*YES*	*YES*
B2	0.000020164	0.00002735	0.737258	*NO*	*NO*

Note: YES - SIGNIFICANCE, NO - NOT SIGNIFICANCE

Table 6.30: The Significance test for Sony Camera 7

	SIGNIFICANCE TEST FOR CAMERA CALIBRATION PARAMETERS				
	CAMERA #		7		
	DEGREE OF FREEDOM		1216		
	CRITICAL VALUE FOR t (95% CL)		1.645		
	CRITICAL VALUE FOR t (99% CL)		2.326		
	PARAMETERS	***STD ERROR***	***CAL t***	***95% CL***	***99% CL***
f	7.3531	0.0009296	7909.961	YES	YES
Xp	0.0368	0.0005621	65.46878	YES	YES
Yp	0.0005	0.0008586	0.582343	NO	NO
K1	0.00311493	0.000009469	328.9608	YES	YES
K2	2.54209E-05	9.774E-07	26.0087	YES	YES
K3	6.05598E-07	2.945E-08	20.5636	YES	YES
P1	5.22758E-06	0.000003548	1.473388	NO	NO
P2	6.29141E-08	0.000002852	0.02206	NO	NO
B1	0.000349173	0.00003147	11.09542	YES	YES
B2	0.000248567	0.0000272	9.138493	YES	YES
	Note: YES - SIGNIFICANCE, NO - NOT SIGNIFICANCE				

Table 6.31: The Significance test for Sony Camera 8

	SIGNIFICANCE TEST FOR CAMERA CALIBRATION PARAMETERS				
	CAMERA #		8		
	DEGREE OF FREEDOM		1198		
	CRITICAL VALUE FOR t (95% CL)		1.645		
	CRITICAL VALUE FOR t (99% CL)		2.326		
	PARAMETERS	***STD ERROR***	***CAL t***	***95% CL***	***99% CL***
f	7.3406	0.0009513	7716.388	YES	YES
Xp	0.0284	0.0005842	48.61349	YES	YES
Yp	0.0395	0.0008891	44.42695	YES	YES
K1	0.00316255	0.00001002	315.6238	YES	YES
K2	3.14694E-05	0.000001057	29.77237	YES	YES
K3	4.94711E-07	3.276E-08	15.10107	YES	YES
P1	0.000145151	0.000003716	39.06109	YES	YES
P2	2.08088E-05	0.00000295	7.053831	YES	YES
B1	0.000455827	0.00003257	13.9953	YES	YES
B2	0.000173792	0.00002834	6.132392	YES	YES
	Note: YES - SIGNIFICANCE, NO - NOT SIGNIFICANCE				

The focal length (f) of all the cameras in general is the most significance parameter as compared to other parameters. The most significance systematic errors are the first radial lens distortion parameter, K_1. Both parameters are calculated to be at a highly significance at both 95% and 99% confidence level.

6.3.3 The Statistical Analysis of Natural Features Technique

As mentioned in Chapter 4 (System Calibration), the accuracy of the stereophotogrammetric system is tested for the measurement of mannequin and real-life human faces. The novel technique known as "natural features technique" is developed to enhance the accuracy of stereophotogrammetric measurement of craniofacial landmarks. The technique is compared with the existing technique namely control frame technique (in slope distance aspect) and the results of the test are shown in section 6.2.2. To prove that the novel technique is different with the existing technique, the F-statistic is used and the result of the analysis is shown in Table 6.32.

Table 6.32: F-test for natural features technique – slope distance analysis on the mannequin

F-Test Two-Sample for Variances

	Control Frame	*Natural Feature*
Mean	4.443	0.612
Variance	17.98635667	0.385062222
Observations	10	10
df	9	9
F	46.71026039	
P(F<=f) one-tail	1.74178E-06	
F Critical one-tail	3.178893105	

With respect to equation (6.1), the null hyporesearch (H_0) is rejected where the different between the two methods is proved to be statistically significance with 95% confidence level. The calculated value for F (46.710) exceeds the critical value of F (3.179) with high significance difference (very small p-value). The similar statistical analysis is carried out to compare both natural features and control frame techniques with the aspect of angle measurements between the test points. The result of the analysis is shown in Table 6.33.

Table 6.33: F-test for natural features technique – angle measurements analysis on the mannequin

F-Test Two-Sample for Variances

	Control Frame	*Natural Feature*
Mean	4.2525	1.8325
Variance	6.136425	0.219691667
Observations	4	4
df	3	3
F	27.93198801	
P(F<=f) one-tail	0.010795088	
F Critical one-tail	9.276628154	

With respect to equation (6.1) too, the null hyporesearch (H_0) is rejected where the difference between the two methods is proven to be statistically significance with 95% confidence level. The calculated value for F (27.932) exceeds the critical value of F (9.277) with p-value of 0.011.

Table 6.34 shows the F-statistical test of the natural features technique where the measurement of the slope distance is carried out on the real-life human faces. With respect to equation (6.1), the null hyporesearch (H_0) is rejected where the different between the two methods is proven to be statistically significance with 95% confidence level. The calculated value for F (8.985) exceeds the critical value of F (3.438) with p-value of 0.003.

From the analysis it can be concluded that the natural features technique is a new technique that can provide more accurate measurement of craniofacial landmark. Compare to the existing control frame technique, the natural features technique needs an additional time to run the triangulation process to obtain the 3D coordinates of the selected natural points.

Table 6.34: F-test for natural features technique – slope distance analysis on real-life human faces

F-Test Two-Sample for Variances

	Control Frame	*Natural Feature*
Mean	2.782222222	0.994444444
Variance	4.245719444	0.472552778
Observations	9	9
df	8	8
F	8.984646042	
P(F<=f) one-tail	0.002743727	
F Critical one-tail	3.438101233	

6.3.4 Statistical Analysis of Optimal Laser Scanning Distance and Focal Length

The analysis is carried out to determine statistically the suitable focal length to be used for the scanning of craniofacial area. The suitability of the focal length is tested on various scanning distances. The F-test is used to carry out the analysis and the results of the analysis is shown in Tables 6.35, 6.36, 6.37 and 6.38 with respect to the scanning distances at 700mm, 800mm, 900mm and 1000mm, respectively.

Table 6.35: F-test for optimal laser scanning distance and focal length (test at distance 700mm)

F-Test Two-Sample for Variances

	Sd = 700(wide)	*Sd = 700(middle)*
Mean	2.587857143	-0.115857143
Variance	1.154912476	0.026152476
Observations	7	7
df	6	6
F	44.16073139	
P(F<=f) one-tail	0.000104998	
F Critical one-tail	4.283865714	

Table 6.36: F-test for optimal laser scanning distance and focal length (test at distance 800mm)

F-Test Two-Sample for Variances

	Sd = 800(wide)	*Sd = 800(middle)*
Mean	2.133571429	0.424428571
Variance	1.270092952	0.175265952
Observations	7	7
df	6	6
F	7.246661061	
P(F<=f) one-tail	0.014744658	
F Critical one-tail	4.283865714	

Table 6.37: F-test for optimal laser scanning distance and focal length (test at distance 900mm)

F-Test Two-Sample for Variances

	Sd = 900(wide)	*Sd = 900(middle)*
Mean	1.975714286	1.097142857
Variance	0.978290571	0.38542081
Observations	7	7
df	6	6
F	2.538240145	
P(F<=f) one-tail	0.140868421	
F Critical one-tail	4.283865714	

Table 6.38: F-test for optimal laser scanning distance and focal length (test at distance 1000mm)

F-Test Two-Sample for Variances

	Sd = 1000(wide)	*Sd = 1000(middle)*
Mean	1.766714286	0.767571429
Variance	0.533861238	0.460175619
Observations	7	7
df	6	6
F	1.160124996	
P(F<=f) one-tail	0.430759484	
F Critical one-tail	4.283865714	

The results of the analysis show that the middle lens with focal length of 14mm are suitable for craniofacial scanning at 700mm and 800mm scanning distances. With respect to equation (6.1), the null hyporesearch (H_0) is rejected where the different between the two focal length is proven to be statistically significance with 95% confidence level. At 700mm, the calculated value for F (44.161) exceeds the critical value of F (4.284) with p-value of 0.0001, while at 800mm, the calculated value for F (7.247) exceeds the critical value of F (4.284) with p-value of 0.015. Among the two tested focal length, the middle lens is found to be the most suitable lens to be used in scanning at distance of 700mm with the higher statistical probability. In other word, the scanning task of the craniofacial surface at this distance (700mm) will delivered high accuracy 3D surface model with maximum point cloud density.

The statistical test has proven that the difference between the two tested focal length at 900mm and 1000mm scanning distances is not significance at 95% confidence level. There is no difference in the accuracy of the scanning 3D model at both distances with either using middle lens or wide lens scanning focal length. At 900mm, the calculated value for F (2.538) is lower than the critical value of F (4.284) with p-value of 0.141, while at 1000mm; the calculated value for F (1.160) deseeds the critical value of F (4.284) with p-value of 0.431.

6.3.5 Statistical Analysis of Laser Scanning Intensity

The F-test is carried out to analyse the significance difference between the laser scanning intensity which is decided to be the most critical factor in scanning craniofacial surface. The results which are shown in section 6.2.5.2, are the graphic evidence to visualise the serious effect of laser intensity on the scanning of craniofacial surface. The statistical test results shown in Tables 6.39 and 6.40 have proven that there is a significance difference between scanning intensity of 20 and 100/150. For the comparison between laser intensity 20 and 100, the calculated value for F (12.185) exceeds the critical value of F (4.284) with p-value of 0.004. For the comparison between laser intensity 20 and 150, the calculated value for F (11.259) exceeds the critical value of F (4.284) with p-value of 0.005.

Table 6.39: F-test for optimal laser scanning intensity (comparing intensity at 100 and 20)

F-Test Two-Sample for Variances

	I100	*I20*
Mean	0.799428571	0.128285714
Variance	1.195463286	0.098105571
Observations	7	7
df	6	6
F	12.18547803	
P(F<=f) one-tail	0.003881065	
F Critical one-tail	4.283865714	

Table 6.40: F-test for optimal laser scanning intensity (comparing intensity at 150 and 20)

F-Test Two-Sample for Variances

	I150	*I20*
Mean	0.640142857	0.128285714
Variance	1.104582143	0.098105571
Observations	7	7
df	6	6
F	11.25911736	
P(F<=f) one-tail	0.00478532	
F Critical one-tail	4.283865714	

6.3.6 Statistical Analysis of Scanning Resolution

Tables 6.41, 6.42 and 6.43 show the statistical analysis results (based on the F-test statistic) for the analysis of optimal scanning resolution, which involve low, medium and high resolution.

Table 6.41: F-test for optimal laser scanning resolution (comparing low and medium resolutions)

F-Test Two-Sample for Variances

	medium	*low*
Mean	0.029571429	0.579
Variance	0.287103619	1.018387333
Observations	7	7
df	6	6
F	0.281919865	
P(F<=f) one-tail	0.074363159	
F Critical one-tail	0.233434021	

Table 6.42: F-test for optimal laser scanning resolution (comparing low and high resolutions)

F-Test Two-Sample for Variances

	high	*low*
Mean	0.178714286	0.579
Variance	0.424616571	1.018387333
Observations	7	7
df	6	6
F	0.416949973	
P(F<=f) one-tail	0.155567917	
F Critical one-tail	0.233434021	

Table 6.43: F-test for optimal laser scanning resolution (comparing medium and high resolutions)

F-Test Two-Sample for Variances

	high	*medium*
Mean	0.178714286	0.029571429
Variance	0.424616571	0.287103619
Observations	7	7
df	6	6
F	1.47896628	
P(F<=f) one-tail	0.323321161	
F Critical one-tail	4.283865714	

The results show that:

- There is a significance difference between low and medium scanning resolution. The calculated value for F (0.282) exceeds the critical value of F (0.233) with p-value of 0.074.
- There is a significance difference between high and low scanning resolution. The calculated value for F (0.417) exceeds the critical value of F (0.233) with p-value of 0.156.
- There is no significance difference between medium and high scanning resolution. The calculated value for F (1.479) is lower than the critical value of F (4.284) with p-value of 0.323.

The above statistical test results show that there is a difference in the measurement accuracy between the measurements on the low resolution scanning 3D model and high resolution scanning 3D model. A similar situation happens in the measurement accuracy between the measurements on the low resolution scanning 3D model and medium resolution scanning 3D model. The test on the scanning resolution comes out with a new finding where there is no difference in the measurement accuracy between the measurements on the medium resolution scanning 3D model and high resolution scanning 3D model. For capturing high density point cloud of craniofacial surface, the high scanning resolution is the suitable choice, but due to the scanning period, which takes longer time to finish the three scans, the medium scanning resolution is the best solution. The statistical test results also concluded that the quality of the 3D craniofacial surface model produced in high scanning resolution are similar to the one that is produced in medium scanning resolution.

6.3.7 Statistical Analysis of Number of Overlapping Scan

Table 6.44 shows the statistical test results for the test on the optimal number of scanning overlap for the scanning of craniofacial surface. The results show that there is a significance difference in the accuracy of the 3D craniofacial surface model that generates using two scans datasets and three scans datasets. The value of calculated F (0.389) exceeds the value of critical F (0.233) with the probability value ($p = 0.138$). But for real scanning situation, two scans datasets (which are required from two sets of laser scanners) is the optimum solution since three scans will required three sets of laser scanners setup in front of the patient during data collection.

Table 6.44: F-test for optimal number of overlapping scan (comparing 3-scans and 2-scans)

F-Test Two-Sample for Variances

	3-scans	*2-scans*
Mean	0.349714286	0.244428571
Variance	0.137870905	0.354197286
Observations	7	7
df	6	6
F	0.389248903	
P(F<=f) one-tail	0.137875409	
F Critical one-tail	0.233434021	

6.3.8 Statistical Analysis of the Integration of Photogrammetry and Laser Scanning Techniques

Table 6.45 show the statistical analysis of the reliability test on the 3D alignment technique for the integration of photogrammetry and laser scanning datasets based on the average distances between the two point clouds datasets. The analysis shows that there is no significance difference between the tests (Test 1, 2 and 3 with different mannequin) and the 3D alignment technique that uses photogrammetric targets as alignment tool is reliable. These are proven where the F critical (*Fcrit*) value wis exceeding the F test statistic value (*F*).

Table 6.45: F-test for reliability of 3D alignment technique for the integration of photogrammetry and laser scanning datasets (test at 99% confidence level)

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
test 1	5	1.346	0.2692	0.0001492
test 2	5	1.199	0.2398	0.0007387
test 3	5	0.943	0.1886	0.0028343

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0166369	2	0.008318	**6.70447585**	0.0111	**6.9266081**
Within Groups	0.0148888	12	0.001241			
Total	0.0315257	14				

6.4 Summary of Results and Analysis

This chapter has successfully described the results of the study and the statistical analysis of the obtained results using advanced statistical analysis methods. As general, the obtained results and results of the statistical analysis are supported the objectives of the study. The summary of the results and analysis are as follows:

- The developed stereophotogrammetric system for capturing stereo images of craniofacial surface is found to be suitable for the task. The calibrated value of the cameras system is highly supported for stereo mapping process. The novel technique known as “natural features technique” is found to be the new technique for high accuracy craniofacial stereo mapping. The technique is significancely different from the previous technique (control frame technique). The combination of the high resolution stereo camera, the high accuracy camera synchronization device and the novel technique allow the achievement of 0.7mm stereo mapping accuracy of the craniofacial landmarks.

- The laser scanner (Minolta Vivid 910) that has been used in the study is found to be suitable for scanning craniofacial surface. The calibration of the scanner has shown that the measurements of the produced 3D models is achieving the accuracy of 0.7mm (or less) with one standard deviation.
- The results and analysis have introduced the detail study of the critical factors and configurations of the scanner for craniofacial mapping, such as scanning distance and focal length, scanning intensity, scanning resolution, and number of scans. The statistical analysis shows that all the factors are important and must be considered when the Minolta Vivid 910 laser scanner are used for mapping craniofacial surface with the measurement accuracy of 0.7mm or less. The findings show that the following parameters are optimal for the factors discussed:
    - Scan distance: 700mm $\pm$100mm
    - Optimum lens: the middle lens
    - Laser beam intensity: auto mode or set the value to between 20 and 40 at normal room lighting
    - Scanning convergence angle: 60^0 to 90^0, best at 90^0
    - Scanning resolution: medium resolution

CHAPTER 7

DISCUSSION, FUTURE WORKS AND CONCLUSIONS

7.1 Introduction

The research consists of two main objectives which are the results of the research. As in general, the objectives have been successfully achieved with high contributions to medical photogrammetric field and craniofacial research especially in Malaysia. Below are the discussions which respect to the objectives and results of the study.

7.1.1 Discussion on a Prototype 3D Craniofacial Imaging System

A unique system and the methods for modeling and measuring craniofacial spatial data using stereophotogrammetry and 3D laser scanning techniques has been presented. The techniques can be applied to measure either the surface of a static craniofacial part (such as dental cast) or the moving surface (such as real life human faces). For the purpose of craniofacial mapping, the developed 3D imaging system provided two types of high accuracy results which are the craniofacial landmarks (measured via stereo images) and 3D craniofacial surface with texture (measured via 3D laser scanning system). The main advantage of both techniques is that it is a non-contact method for measuring craniofacial landmarks and modeling of craniofacial surface. The developed 3D imaging system is highly beneficial to craniofacial research in Malaysia where in general practice, the calipers and the mold are used to measure craniofacial landmarks and to develop the physical 3D surface of craniofacial, respectively.

The accurate measurement of craniofacial landmarks starts with an adequate acquisition of the required data. In this study, the multi-stereo imaging system is developed to acquire complete craniofacial stereo images (from left ear to right ear and from hair line to bottom part of the chin). In the later case, it is obvious that the multi-stereo images have to acquire simultaneously. The precision of the synchronisation of the multiple imaging devices plays an essential role in the accuracy of the measurement. For that purpose a specially built synchronisation device is developed to synchronise multiple high resolution (8 mega pixels) digital cameras to acquire multi-images simultaneously. However, the device has a limited synchronisation capability. The maximum delay which can occur between the acquisitions of the different images is 0.2 milliseconds. However the synchronisation delay is accepted to be used in the system as the eyelids blink at a velocity of about 205 $mm \ s^{-1}$ and it takes about 0.22 seconds for the eyelid to complete a cycle. With 0.2 milliseconds synchronisation delay between the cameras, the systematic error due to the movement of the face is minimum. In comparison with the other imaging system which is based on the synchronisation of the charge couple device (CCD) cameras, the maximum synchronisation time delay is half a frame (0.04 seconds). Therefore the developed imaging system enhances the synchronisation accuracy with 0.2 milliseconds. This device is a new contribution in medical phoogrammetric imaging field.

With high accuracy synchronisation external device and eight high resolution digital cameras (Sony DSC F828), the complete cost for the stereo camera imaging system is RM 50,000 approximately. A similar system with 5 mega pixels Sony V1 digital cameras which is used at School of Dental Sciences, University of Science Malaysia, Kubang Krian, Kelantan, the cost is about RM 14,000, approximately. Based on the estimated cost, the developed imaging system is considered as a low cost stereophotogrammetric data acquisition system for craniofacial mapping.

With the capability of high accuracy synchronisation of the stereo camera system, the accuracy of measuring craniofacial landmarks is enhanced by introducing the natural features technique which applies natural features as control points for stereophotogrammetric mapping of craniofacial stereo images. The eight images acquired from eight digital cameras are used to digitize the natural features and to perform the photogrammetric triangulation process in order to gain the 3D coordinates of the natural features. Subsequently, the 3D coordinates is used in the stereophotogrammetric workstation to perform the absolute orientation process. The natural features technique is considered as a "novel" technique (Majid et.al, 2006) to increase the accuracy of craniofacial landmarks measurement using stereo images. The overall results show that the accuracy of 0.65mm to 0.8mm with one standard deviation can be successfully achieved by the proposed technique. By using the natural features technique, there is no need to change the setup of the stereo camera system and to shorten the camera-object distance. With high resolution pixels, good quality natural features are easily found and they are well-distributed in the stereo overlapping area.

The developed stereophotogrammetric system can be used to acquire craniofacial spatial data from city to rural area without any problem with distributed power supply. This is because the system is fully design to be operated with battery system. The power of the synchronisation device is generated from battery used by the cameras. The system can be considered as the first photogrammetric data acquisition system, setup as multi-cameras that operate using battery system.

The use of 3D laser scanning system in modeling and measuring craniofacial surface is found to be excellent and effective. The main idea involving 3D laser scanning in the Malaysian craniofacial data acquisition system is to acquire 3D surface model of the craniofacial. The idea is excellent because the 3D surface model can be acquired within 0.3 second because in comparison with the other 3D surface imaging system which is based on multi-cameras and image matching method, and which take longer time to produce the 3D model even the setup system is fully automated (D'Apuzzo, 2003). In the system developed by D'Apuzzo, the random pattern is projected onto facial surface before the cameras capture the images. By using the 3D laser scanning system, there is no need to project any pattern or grid onto the face since the system is based on structured light triangulation technique.

The eye-ball, the hair and other black features, such as eye-brow, are not successfully scanned by the scanner in optimum laser intensity (Majid et. Al, 2004). However, the problem is not important since the location of the craniofacial landmarks is on the skin area. The 3D surface model generated by the laser scanner is also available for measuring craniofacial landmarks. The landmarks are digitised directly to the 3D facial surface and the 3D coordinate of the landmarks is recorded by the software. By using the appropriate software, three types of measurements can be performed on the 3D surface model generated by the laser scanner. The measurements are straight line (direct), along the surface and angle. The results of the measurements show that the difference between the caliper method and laser scanning method is range from 0.2mm to 0.8mm. The measurement of the landmarks using 3D laser surface model is found to be faster than the measurement using stereo images, although both techniques performed the measurement in three-dimensional environment.

The Minolta Vivid 910 laser scanner is built with RGB filter in order to capture the texture of the craniofacial. The texture is automatically registered onto 3D surface during scanning process. The need of the texture is essential in the prediction of the location of the craniofacial landmark on the 3D surface model. In comparison with the 3D stereophotogrammetric system developed by D'Apuzzo, the texture data is captured using extra video camera setup in-front of the subject. The texture is only mapped onto 3D model just after the 3D reconstruction process. The 3D craniofacial surface model with texture can be exported in various 3D modeling format such as igs, ascii and etc. The physical model can also be produced using rapid prototyping (RP) technology.

In general, as compared to other developed system for craniofacial mapping, the Malaysian Craniofacial Imaging System developed in this study is unique especially the stereophotogrammetric system. With the development of a new multi-camera synchronization device, it indirectly rejects the opinion given by D'Apuzzo who mentioned that the precise synchronisation of multiple imaging units is possible only by the machine vision acquisition system.

7.1.2 Discussion on System Calibration

The lens and optical system of the camera and the laser scanner also play a role for the quality of the acquired craniofacial spatial data. As mentioned earlier, the developed 3D imaging system in this study consists of two 3D imaging sensors which is stereo-camera and 3D laser scanner. For the purpose of high accuracy data acquisition, both sensors are calibrated individually. To calibrate the multi-stereo imaging system, various methods can be used. Each digital camera is photogrammetrically calibrated using self-calibration bundle adjustment method. A new device so called camera calibration test field is successfully developed. The test field allows the calibration process to be carried out with fixed object distances for each exposure. The external shutter is used in order to avoid the movement of the camera during exposure. The calibration test field consists of 800mm x 800mm wood with different depth of 100 3mm retro targets. The highest depth is 60mm which is 10% of object distance (the distance between camera to subject). The results of the calibration consist of the bundle adjustment results, the corrected camera parameters and the corrected 3D coordinates of the 100 retro targets. The accuracy of the calibration is increased by using the precise scale bar. The design of the new calibration test field is essential in order to make sure that all the targets appeared in four images or more. This rule is compulsory in order to achieve the higher accuracy of the photogrammetric measurement. For the purpose of craniofacial mapping, the focal length, the principal point coordinates and radial lens distortion are taken into account. The decentering distortion and the CCD flatness are rejected since the value is too small and it is assumed that the errors due to those parameters are rejected.

The Minolta Vivid 910 3D laser scanner is also calibrated to verify the correctness of the 3D model generated from the scanner. In principle, the scale of the computerized 3D model and the real model is 1:1. According to Majid et. al (2006), the calibration is carried out for three reasons: (a) the scanner can give the accuracy that needed for various types of object shape, object size and surface texture; (b) the processing method give the correct measurement; and (c) the calibration data is needed to show the mapping product are accurate within the project specifications. Three types of object are used to calibrate the laser scanner and the measurement of the test points setup on the surface of the object are also measured using close-range photogrammetric technique. The results of the calibration show that Minolta Vivid 910 laser scanner satisfies the accuracy required for craniofacial mapping project. The test on the three test object shows the accuracy of the laser scanner is higher with standard deviation of 0.1mm to 0.2mm.

The calibration of the 3D laser scanning system is ended by a complete study of the important considerations of using the scanner for craniofacial mapping (Majid et. al, 2006). Various parameters have been studied and the results shows that the accuracy of craniofacial mapping using laser scanner is a function of five scanning parameters such as laser beam intensity, number of scan per craniofacial area, the focal length of the CCD lens, the scan distance and the scan resolution. In general, for mapping craniofacial using laser scanner, the optimum laser intensity is 20 to 40, the optimum resolution is medium resolution, the optimum number of scan per craniofacial area is two scan (one from each scanner), the optimum scanning distance is from the range of 700mm to 800mm and the optimum lens is medium lens with 14mm focal length. The scanned angle factor becomes an important factor when two laser scanners are used to capture craniofacial area. The study shows that the optimum scanning area is from the range of 80^0 to 90^0. Such angle is needed in order to acquire 3D surface model of the craniofacial area with complete shape of ear. It is important to map the ear because part of the craniofacial landmarks is located on the ear.

7.1.3 Discussion on Alignment of 3D Point Clouds using Photogrammetric Targets

For precise mapping of craniofacial area, especially with 90^0 scanning angle, a new method is introduced to align the 3D point clouds datasets with high accuracy alignment process. The method performs the alignment of the two scans data, by using the photogrammetric targets that are well distributed arround the craniofacial area. The test on the mannequin shows that the accuracy of the 3D model of the mannequin is 0.13mm to 0.28mm, while the accuracy of 3D model of real life human faces is 0.21mm to 0.27mm. These results improve the accuracy of the 3D model generated from the corresponding features method which is reported to be 0.3mm to 0.7mm (Kau et al (2004), Kau et al (2005), Kau et al (2006)).

In general, the involvement of the new method for aligning craniofacial scans data does not affect the initial setup of the developed craniofacial data acquisition system. The changes are needed on the photogrammetric control frame where the paper targets are needed as photogrammetric targets for the execution of the method. The used of paper targets in the new method is compulsory to avoid the reflection error due to the laser light, which is generally happens to retro targets. The changes are also needed for the scanning distance where we have to increase the scanning distance in order to capture the photogrammetric targets. From the experience, the optimum scanning distance to execute the method is 1300mm with wide angle scanning lens.

The results also show that the new method can be used to detect the movement of the craniofacial area during the scanning process. Experience with other registration methods such as corresponding features method, the photogrammetric targets method is the only method that is very effective to use in the detection of error in the 3D model due to the movement of the subject.

7.2 Suggestions for Further Works

This study allows for further works as the continuation of the findings. The propose further works are given below:

7.2.1 Further Works on a Prototype 3D Craniofacial Imaging System

For further research, the prototype 3D craniofacial imaging system requires some changes especially for the 3D laser scanning system which takes about 19 seconds to complete the medium resolution scans of craniofacial area. The scanning time is considered too long which can introduce error in the scanning datasets due to the movement of the face. The problem appears when the two Minolta Vivid 910 laser scanners begin the scanning process one after another. The problem can be solved if scanning period from the two laser scanners can be reduced. A research is needed to synchronise the two laser scanners. As a rough calculation, each scanner takes about 9.5 seconds to complete the scanning process. A synchronisation of the scanners can be carried out by having a second scanner performs the scanning one second just after the first scanner starts the scanning process.

The research on the craniofacial imaging can be improved by integrating the developed imaging system with other craniofacial imaging modalities such as near infrared (NIR) camera, magnetic resonance imaging (MRI) scanner and computed tomography (CT) scanner. With the developed craniofacial imaging system, the soft tissue of the craniofacial surface is successfully captured and measured. The drawback of the system is the lacked of craniofacial hard tissue data which is the most important data in craniofacial reconstruction task. MRI and CT scanners gain the strength to capture the craniofacial hard tissue data in three-dimensional mode. Both soft tissue and hard tissue datasets can be integrate for high accuracy surgical planning purposes. The research may involve the development of a new registration technique to integrate both soft tissue datasets captured using the developed imaging system (stereophotogrammetry and laser scanning system) and hard tissue datasets (capture using MRI and CT scanners).

7.3 Conclusion

The objectives of the research have been successfully completed. The developed craniofacial imaging system is a unique system. It is also the first system in Malaysia in order to replace the conventional method for modeling and measuring craniofacial surface. The effectiveness of the craniofacial imaging system is enhanced by the development of a "novel" natural features technique for measuring craniofacial landmarks via stereophotogrammetric technique. The strength of the system is also enhanced by the use of 3D laser scanner for fast and high accurate 3D surface model acquisition. As far as the state of the art in craniofacial soft tissue imaging, the developed system, which combined stereophotogrammetry and 3D laser scanner, is considered as a new data acquisition approach. This is because, for each craniofacial patient, two types of spatial data are acquired.

The research also involves the calibration of the developed 3D imaging system. Both stereo-cameras and 3D laser scanners are accurately calibrated for the study of errors in the system that can effect the accuracy of the craniofacial spatial data. New devices and new calibration approach are developed and implemented in the calibration process. In addition, a new approach for the high accuracy alignment of 3D laser scanner point clouds datasets by using photogrammetric targets is also developed. The test of the approach proves that the accuracy of the alignment process is improved as compared to the conventional practice of using corresponding features technique.

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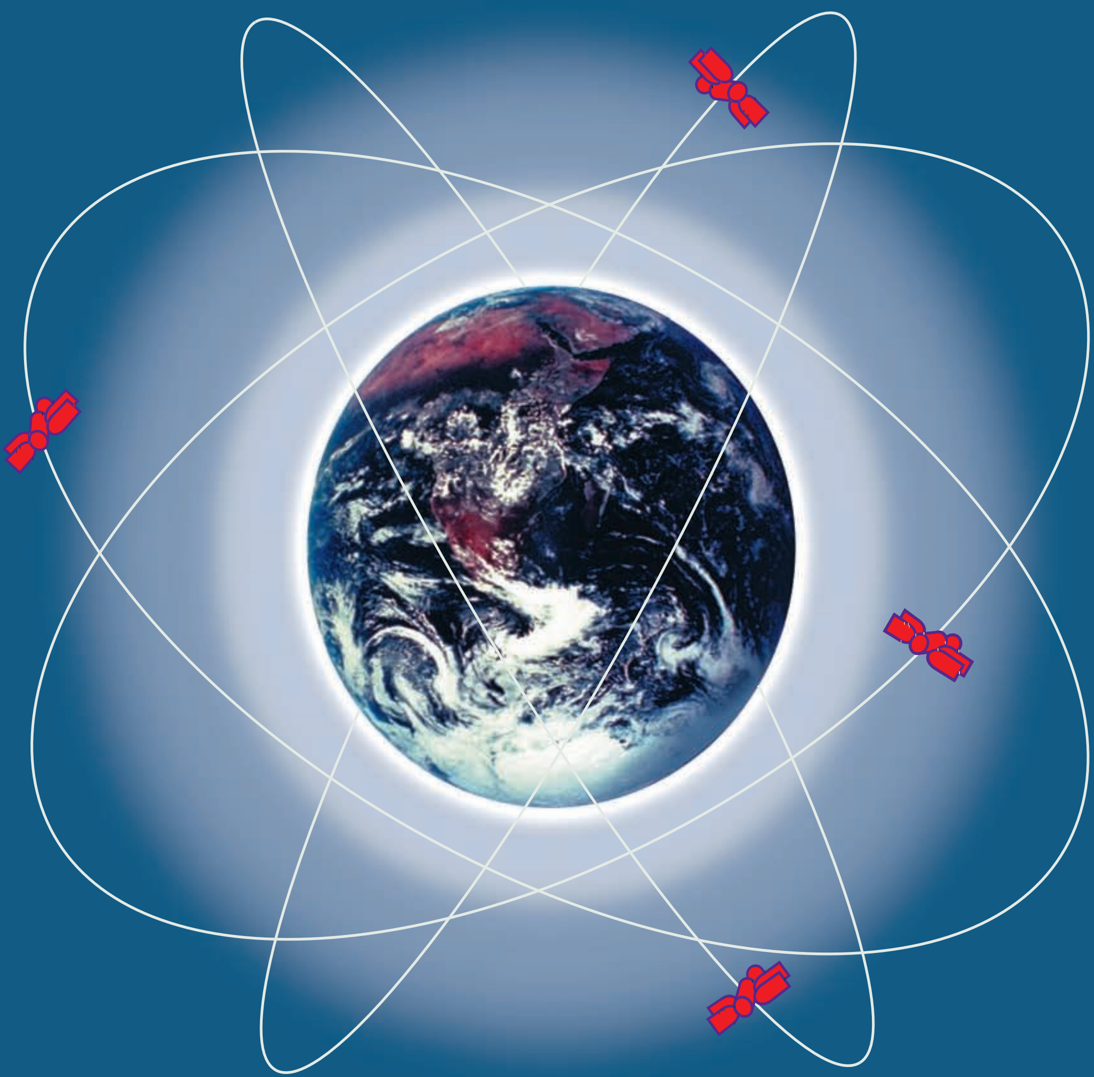

- A young surveyors group
- Craniofacial stereo mapping: Improving accuracy with natural points
- Dealing with priceless treasure: comparing land with customary links
- Back to the land: Walking access to the outdoors
- Zones of confidence for New Zealand
- Boundary systems in informal settlement upgrades: Imizamo Yethu settlement in Cape Town

NEW ZEALAND INSTITUTE OF SURVEYORS

A body for the advancement of the profession of surveying, dedicated to the service of its members and society by:

- *Representing the public interest*
- *Promoting ethical professional conduct amongst its members*
- *Advocating standards for surveying education; and*
- *Raising public awareness of the knowledge, skills and experience of surveyors.*

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Editor
A J Baldwin
School of Surveying
University of Otago
PO Box 56
DUNEDIN

Phone: (03) 479 7595
Fax: (03) 479 7586
Email: john.baldwin@otago.ac.nz

Correspondence relating to literary items in New Zealand Surveyor may be addressed to the editor. Papers, articles and letters to the editor, suitable for publication, are welcome.
All correspondence relating to business aspects, including subscriptions and advertising, should be addressed to:
The National Manager
New Zealand Institute of Surveyors Inc.
PO Box 831
Wellington
NEW ZEALAND

Phone: (04) 471 1774
Fax: (04) 471 1907
Email: nzis@surveyors.org.nz
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REFEREE PANEL

COVER PICTURE

The cover continues our global theme and shows a view of planet earth from outer space encircled by a constellation of stylised satellites. This symbolises the global nature of surveying; the development of the Global Positioning System which succeeds through international co-operation and the New Zealand surveyor working throughout the world.

EDITORIAL

A young surveyors group

JOHN BALDWIN

Editor

An outcome from the 117th AGM and Conference in Dunedin was the decision to establish a Young Surveyors group within the Institute. This is a timely move as we see the diverse career options being taken up by recent Bachelor of Surveying graduates. When divisions were first established within the Institute there were distinct employer groups – the Local Government Surveyors (who did much planning work as well as surveying), the State Sector group, which included surveyors particularly from Lands & Survey/DoSLI, Ministry of Works and Forestry, and the Consulting Surveyors, private practising surveyors who had an ownership interest in a private firm.

Times have changed. With automation and contract work the state sector has shrunk to the extent that the group closed. Although with the advent of the RMA and the reorganisation of local government to districts and cities, planning work has increased, but there has been a steady decline in the numbers of surveyors attracted to the councils. The active but gradually shrinking Local Government group has continued to provide hugely valuable annual seminars that are now accepted as important to any land professionals dealing with local government. The loss to local government, generally through retirements and loss of status of the surveyors there, with the wide knowledge of subdivision and pragmatic understanding of land development has its own adverse cumulative effects.

On the positive side, the consultants' division, Consulting Surveyors of New Zealand (CSNZ) has flourished. CSNZ was established for members with financial interests in surveying firms to meet and talk business as much as technical surveying. This has seen vital and valuable development and learning in the way surveyors act as professionals frequently dealing with all aspects of extensive multi-million dollar development projects. The annual CSNZ workshops have become increasingly popular and for a variety of reasons, produce attendance numbers similar to the Institute's AGM and Conference.

For several years now, graduates have readily found employment within private practices, with consultants, but not being directors, partners or managers have lacked their own special interest group. The adoption of the premier title Registered Professional Surveyor (RPSurv) does provide a convenient interest grouping for more senior professionals who may not be involved with business management.

The formation of NZIS Young Surveyors should rectify the lack of a special interest group for the recent graduates. With the new rules for membership and the wide scope of disciplines, broadening the career path opportunities, it is vital that the Institute nurtures and fosters these graduates. Their career paths beyond university may never include any cadastral work, which until the 1990s was the fundamental core of most graduates' early employment.

The Institute should flourish if it can provide encouragement and appropriate continuing professional development opportunities for the diversifying career paths. The young surveyors have ample talent within their ranks but it is the synergy that support from the Institute can provide that will allow the most effective progress.

Over the next few months, Young Surveyors will be constituted as a formal Institute grouping. It is expected that the group will comprise predominantly graduates members, especially those who are working to expeditiously successfully complete their membership admission and proceed to RPSurv status. Age was not seen as a criterion for being a Young Surveyor because there are a number of mature graduates. However, it is likely that once a member has reached RPSurv status their efforts and energies might be directed to other activities within the Institute. Already there has been some self-help with young surveyors groups in some branches organising pre-exam Acts and Regulations sessions that markedly improved the pass rate to nearly 80% of the record 88 candidates.

The desire of young surveyors to establish their own group is an encouraging sign of development within the new broader Institute as we move to promote and develop the diverse skill sets of NZIS members. The formation of this new generation group is especially welcome when one inspects the membership lists later in this issue, Retired Members, whose continuing support we value highly are a significant proportion of the Institute. The Young Surveyors group needs support and encouragement for the Institute to thrive and become a prominent Institute group.

ZULKEPLI MAJID

Halim Setan and Anuar Ahmad
Faculty of Geoinformation Science & Engineering, Universiti Teknologi Malaysia

ALBERT CHONG

School of Surveying, University of Otago, Dunedin, New Zealand

Craniofacial stereo mapping: Improving accuracy with natural points

ABSTRACT

Stereo-photogrammetry has been reported in both photogrammetry and medical journals as the most suitable technique for craniofacial landmark mapping. Various size and shape of control frames were designed to provide three-dimensional object-space control for stereo images. A research was carried out to determine whether the accuracy could be further improved using natural points. In the research, control points and natural points were measured using photogrammetric digitising software and their coordinates computed using bundle adjustment technique. In addition, the six-camera stereo-photogrammetric system was electronically synchronized for optimum accuracy. Subsequently, a digital photogrammetric workstation was used for stereo orientation and stereo-digitising of the anthropometric landmarks. For the accuracy assessment of the 'natural point' technique, absolute orientation was performed on the stereo-model using control-frame control and natural points respectively. The results show that the developed technique achieves an accuracy of 0.6mm at one standard deviation. The best accuracy of the stereophotogrammetric system was 0.25mm.

ALBERT K. CHONG

Albert received his diploma in surveying from Auckland Technical Institute, Auckland. Subsequently, he moved to the USA where he completed a PhD in photogrammetry at the University of Washington, Seattle. He has taught at the University of Washington and Ferris State University, Big Rapids, Michigan.

Albert has published over 80 technical papers in surveying, photogrammetry and spatial information technology. Albert's current major research interest is in the field of medical photogrammetry – craniofacial mapping; effect of rigorous exercise on spinal cord and swallowing coordination.

ZULKEPLI B. MAJID

Zul is a lecturer at the Faculty of Geoinformation Science and Engineering at Universiti Teknologi Malaysia, Johor Bahru, Malaysia.

He specialises in medical photogrammetry and laser scanning technology. He has received a number of awards for excellence in teaching and research. Currently, he is completing his PhD in medical photogrammetry under the supervision of Professor Halim B Setan (UTM) and Dr Albert Chong (University of Otago).

INTRODUCTION

Craniofacial anthropometric measurements required high quality measuring tools in order to obtain the highest possible measurement accuracy (Farkas et al. 1996). Among the methods used, Stereophotogrammetry was chosen as the best as a non-contact, non-invasive, reproducible, fast, high-accuracy, practical and cost-effective technique measurement of facial morphology (Naftel et al. 2004; Burke et al.1983; Hay et al. 1985; Majid et al. 2005; Meintjes et al. 2002; Ras et al.1995; Wagner et al. 2005; Johnston et al. 2003).

Generally, object-space control is required for the stereo orientation of the craniofacial stereo-photographs. The control allows scaling and orientation of the spatial three-dimensional model during absolute orientation. The control frame may be placed over the patient's head (Savara and George 1984); near both side of the head (Peterson 1993) and (Schewe and Ifert 2000) the control targets were placed on a helmet. These three designs almost certainly covered in all published photogrammetric control configurations (Majid et al. 2005). However, tests show that the recommended location of the control targets on the frame was not suitable for high accuracy stereo-orientation. The accuracy in the Z (along the optical axis) does not satisfy the project requirement of 0.7 mm where the Z position of the landmark is far from the average Z position of the control points (Ghosh 1972: p41). For example, the Z value of the nose is outside the Z zone controlled by the control-board control (Figure 1). The research is to solve the problem by testing the suitability of using natural points, which may be birth mark, acne or scar, as control for stereo-orientation.

Consequently, a method was developed to

obtain accurate coordinates of the natural points. It involves a bundle adjustment of six stereo-photographs taken for the three stereo-models using the control frame. The bundle adjustment computes the coordinate of the natural points. Subsequently, the natural points are used to carry out exterior orientation of the stereo-models.

The objective of the paper is to present the developed technique. The discussion includes: 1) computing the coordinate of the natural points; 2) model orientation using the natural points and 3) analysing the accuracy of the technique by comparing the Z coordinate obtained by the natural points with those obtained by using the control frame.

METHODOLOGY

Stereo-photography

The design of the photography is based on three stereo-pairs of photograph. Six Sony DSC F828 digital cameras were set up 600 mm from the object (mannequin and human face) to capture the stereo images. The cameras were electronically synchronized using a lanc shepherd controller (Graphic Media Research, Minnesota, USA). Figure 1 shows the setup of the stereo-photographic system at School of Surveying, University of Otago.

Calibrating the stereo camera

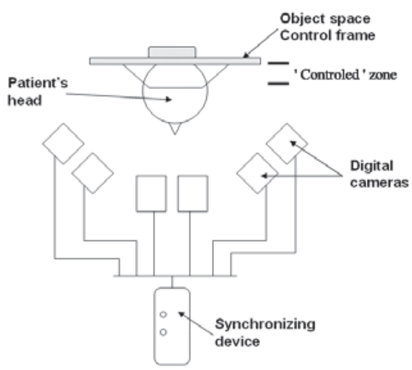

Figure 1: Stereo-photographic system used in the study. Note the distance (Z) from the nose to the control frame and the control zone.

Each camera was calibrated independently using a three dimensional calibration device (Figure 2). The device consists of a camera mount and a 3D test field. Retro-targets were placed in row and column as shown in the figure. The calibration procedure is discussed in Chong and Scarfe (2000) and Majid et al. (2005).

Calibrating the photogrammetric control frame

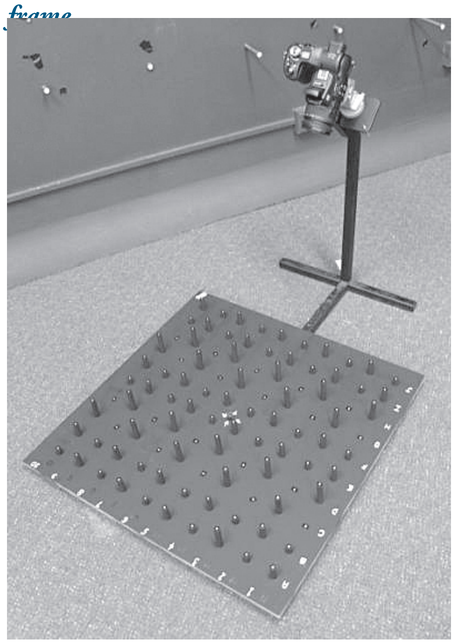

Figure 2: A three dimensional camera calibration test field.

A control frame was built to provide an accurate control for the research (Figure 3). Retro-targets were used to highlight the control points. The control frame also

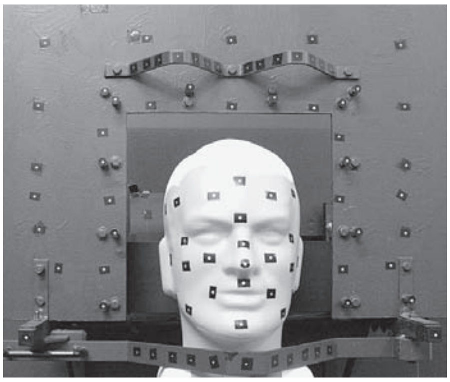

Figure 3: A high-quality control frame with control points and the simulated natural points on the face (both marked with retro targets). Note that the simulated natural points were also used as a test point for distance and angle measurements.

requires accurate calibration. The x, y and z coordinates of the targets were determined using convergent photographs and a bundle adjustment (Chong and Strafford 2002). The coordinates would be used for the exterior orientation of the stereo models and for computing natural points' coordinates.

Data collection

The photography consists of two stages: (1) a set of convergent photographs of the mannequin to determine coordinates of the simulated natural points (see Figure 4) and (2) a set of six stereo-photographs of the mannequin for stereo-digitising of the anthropometric marks and 3D surface (see Figure 5 and Figure 6). In stage (1), six convergent photographs were captured. A scale bar which consists of an invar bar with a target at each ends, was placed in the object space. Stage (2) involved the capturing of 60% stereo-photogrammetric overlap of the mannequin from three different stereo camera positions which covered the craniofacial area. The camera

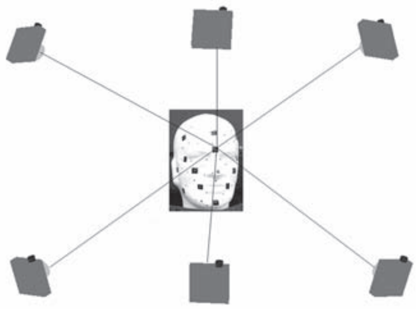

Figure 4: Convergent photographs for the bundle adjustment of the test point coordinates. Note that the photographs were not used for stereo-digitising on photogrammetric workstation.

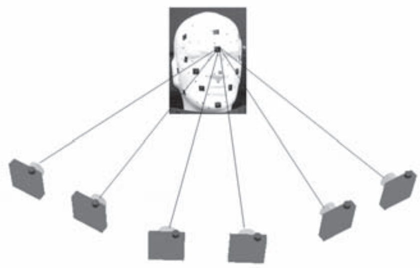

Figure 5: Normal stereo-photographs for stereo-digitising of the anthropometric marks. Note the camera configuration and the bundle of rays to the natural point and test points.

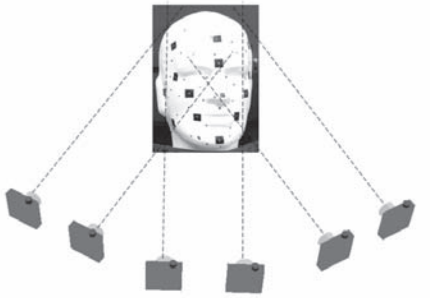

Figure 6: The stereo photographs of the test object showing the overlap areas. The configuration is also shown in Fig. 1.

lens to object distance (object distance) was set to 600 mm.

Data processing

There are four stages for this part of the research. The stages are discussed below.

i) Stage 1: *Obtaining object-space coordinates of control frame points.*

Australis photogrammetric software was used to mono-digitise image coordinate (x and y) of the retro-targets on the control frame and test points on the six convergent photographs. Retro-target on the scale bar were also digitized. A bundle adjustment was performed on the image coordinates of the digitized points using Australis. The scale bar was used in the adjustment to scale the object-space coordinates. The output of the adjustment is a set of accurate coordinates for the control and test points.

ii) Stage 2: *Obtaining object-space coordinates of the natural points.*

Also mono-digitising was performed on all six stereo-photographs. However, natural points were added to the list of points for digitising. The scale bar targets were not observed because the object-space would be scaled by control-frame coordinates which were obtained in Stage 1. A bundle adjustment was performed on the image coordinates of the observed points. It must be noted that a triangulation must be carried out if there are very few observed points. This is because the bundle adjustment requires an appropriate number of degrees of freedom to achieve a high quality Least Squares solution.

iii) Stage 3: *Obtaining object-space coordinates of test points using stereo-digitising technique.*

The Stereo Orientation module, DVP software (DVP, Canada) was used to establish stereo-orientations (interior, relative and absolute) for stereo-digitising and the vectorisation module was used to obtain the 3D coordinates of the test points (Figure 7). In this study, the stereo-models (front view, left view and right view) were processed separately. Absolute orientation of each model involved two separate sets of three-dimensional ground controls, namely: (a) signalised targets on the control frame; and (b) signalised targets on the face or natural points. After each absolute orientation, the 3D coordinates of the test points was measured three times stereoscopically and the average of the coordinates was calculated

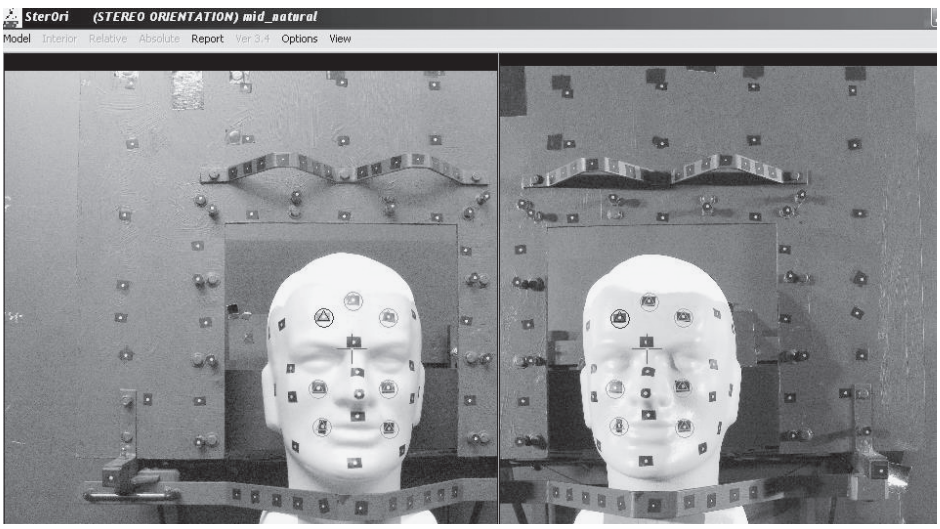

Figure 7: Stereo digitising of test points using DVP software.

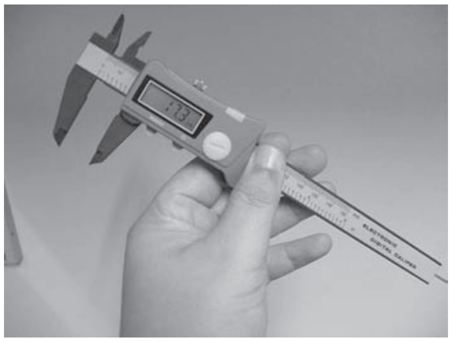

Figure 8: A digital calliper used for direct measurement on the mannequin.

for comparison.

iv) Stage 4: *Obtaining 3D distances between test points using calliper technique.*

The digital calliper with the accuracy of 0.1mm was used to measure the distances between the selected test points on the craniofacial surface directly. The calliper was calibrated to ensure accurate measurement. Each distance was measured three times and the average of the distances calculated. Figure 8 shows the digital calliper used in the measurements.

RESULTS AND ANALYSIS

The accuracies of measurements of the control frame and the natural point methods were first determined by using standard errors of control coordinates in the absolute orientation. The standard error depends on the accuracy of three-dimensional ground control coordinates and the location of the control on the model. Table 1 shows the standard errors obtained from the methods. The control was well distributed on the stereomodel. The results show a significant improvement in the size of the error.

Further analysis involved studying the vector, distance and angle measurements between sets of test points. In the study, the distances and angles obtained by an independent method (bundle adjustment method) was used as a *gold standard* to verify the accuracy of the techniques. Also, the analysis involved the comparison of the Z values of the stereo-photogrammetric measurements obtained by the techniques.

(a) Analysis of the 3D distance and angle

Table 1. Optimum standard error of stereo-photogrammetric absolute orientation.

Methods	Standard errors in x, y and z axis. (mm)
Control frame method	Front model (0.347, 0.303, 0.533)
	Left model (0.364, 0.225, 0.266)
	Right model (0.304, 0.222, 0.237)
Natural point method	Front model (0.063, 0.117, 0.246)
	Left model (0.125, 0.112, 0.310)
	Right model (0.216, 0.112, 0.320)

The analysis involved sixteen anthropometric points which were marked by signalised targets (Fig. 9). There were four types of measurement obtained from four techniques. The techniques were: 1) independent bundle adjustment; 2) control frame method; 3) natural point method; and 4) caliper method. Independent bundle was used as the gold standard. The comparison was carried out using the mean, variance and standard deviation of the measurement difference. Tables II and III show the results of the analysis.

(b) Analysis of depth value

The study of the depth value in the research was to prove that the use of natural points as object-space control for craniofacial stereo-photogrammetric mapping improves the accuracy of anthropometric landmark measurements. The depth value is defined as the height difference between the average datum (the average height of all object-space controls of a model) to a measured points (e.g. anthropometric landmarks). The depth percentage (%) is the ratio of the depth value and the object distance in percents. As discussed elsewhere, in aerial stereo-photogrammetric mapping, the terrain height variation should not be more than 10% of the flying height in order to obtain accurate height measurements (Ghosh 1972: p41). The requirement should be applied to close-range stereo-photogrammetry. That is, the computed height of a measured points in a stereomodel would have an accurate height if the depth value of the point is within ±10% of the object distance. For example, for the object distance of 600mm, the optimum depth value is ±60mm. In the analysis, the depth percentage and the depth value of measured test landmarks for both techniques were examined (Figure 10).

The statistical analysis involved two variable regressions between the errors in z coordinates versus the depth percentage for each test point in both methods. The plots of the results are provided in Figure 12 and Figure 13. Both plots show consistent results in which an increase of depth percentage there is an increase in the error of z coordinate. The results also show that the natural point method is more accurate than the control

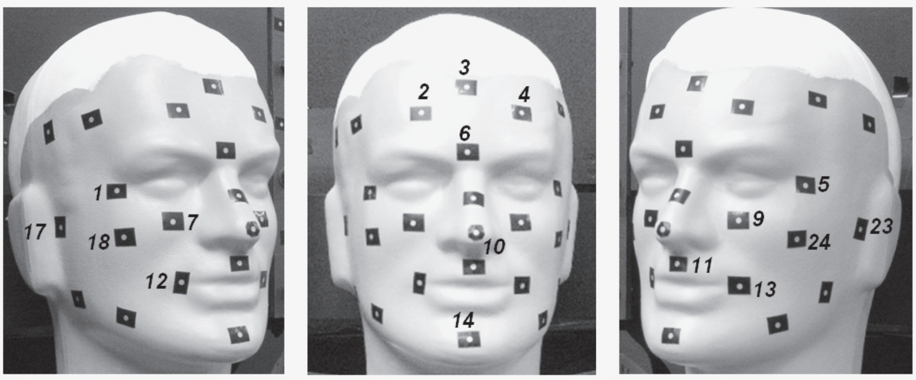

Fig. 9. Position of anthropometric points on the mannequin.

Table 2: Distance measurement differences.

From point	To point	Calliper vs. bundle method (mm)	Natural point method vs. bundle method (mm)	Control frame method vs. bundle method (mm)
2	4	0.18	0.08	1.72
3	6	0.35	0.44	0.36
6	10	0.21	1.44	0 .5
12	13	0.11	0.50	4.85
1	5	0.11	0.61	7.66
17	7	0.20	0.37	10.20
9	23	0.15	2.00	12.22
4	24	0.11	0.12	0 .90
2	18	0.17	0.34	2 .16
3	14	0.32	0.22	3 .86
Statistics	*Mean*	***0.19***	***0.61***	***4.43***
	Variance	***0.01***	***0.38***	***18.07***
	Std Dev	***0.08***	***0.62***	***4.25***

Table 3: Angle measurement differences. Note that the calliper measurement excluded the angles not measured physically.

Three points involved (first – middle – last)	Natural point method vs. bundle method (deg)	Control frame method vs. bundle method (deg)
5-23-13	2.04	1.81
1-17-12	2.08	2.44
3-17-14	2.08	6.61
3-23-14	1.13	6.15
Mean	***1.83***	***4.25***
Variance	***0.16***	***4.60***
Std Dev	***0.40***	***2.14***

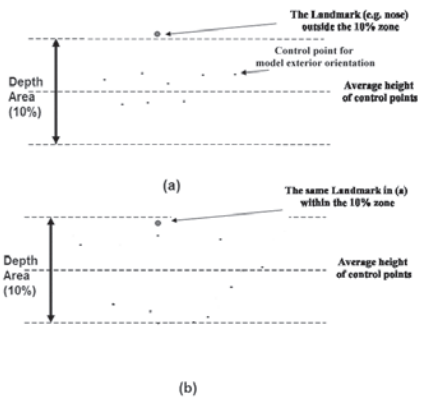

Fig. 10. Location of test landmarks and the average height datum of (a) control point method and (b) natural point method.

frame method.

An F statistic test was conducted to verify the accuracy of the natural point method. The test involved the analysis of population variance to test the significance of difference between the two methods. The null hypothesis (the accuracy of the two methods are the same) was tested. The null hypothesis was rejected and it proved that the accuracy of the two methods is not the same. In other words, natural point method is more accurate.

CASE STUDY

To verify that the developed method was really accurate to support the craniofacial anthropometric mapping, a facial surface with signalized target (representing natural points and test points) was used in the case study (see Figure 14). The face, control frame and photography using the six synchronized digital cameras were a duplicate of the previous test study (Figure 1). Photogrammetric

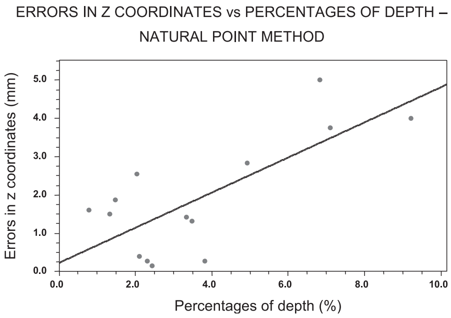

Fig. 11 Depth percentage analysis – natural point method.

triangulation method was used to calculate the three dimensional coordinates of the signalized target accurately using Australis software. Both control frame and natural point method were carried out separately in the exterior orientation of the three pairs of stereo models. Nine 3D measurements between targets were performed stereoscopically. The direct measurements were also performed using calliper as a comparison with the proposed method. All the measurements were repeated three times in order to make sure that each technique was reproducible.

Table 5 shows the results of study. The natural point method was found to be more accurate with standard deviation of 0.65 mm compared to 1.94 mm from the control frame method.

DISCUSSION

The use of natural point's method as a object-space control was found to be an effective method to improve the accuracy of the craniofacial stereo mapping. By using the natural points method, there is no need to shorten the camera-object distance. Consequently, the optimum coverage of

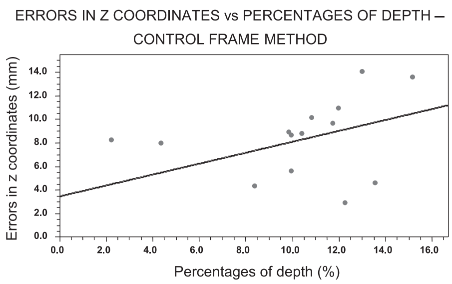

Figure 12: Depth percentage analysis – control frame method.

three models for the craniofacial area was maintained as designed. Good quality natural points were easily found and they were well-distributed in the overlapping areas.

Only an additional one hour was needed to run the triangulation process to obtain the 3D coordinates of the selected natural points. Australis camera calibration software was used to digitize the natural points and to run the triangulation adjustment. Since the same software was used for calibrating the stereo cameras, digitising the points and computing the coordinates of the natural points, there is no additional cost involved.

CONCLUDING REMARKS

Research is in progress to use the natural points method for the living craniofacial patients. In addition, tests are being carried out on the use of near infrared filter for the high accuracy of natural points identification and measurements. The results of the research will be published in near future.

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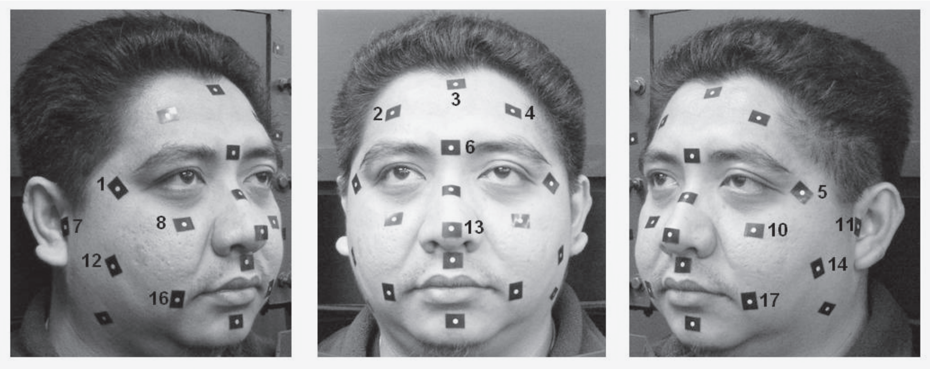

Figure 14: Human face with signalised targets to represent the natural points and test points.

the Ministry of Science, Technology and the Environment (MOSTE) Malaysia for this multi-million dollar craniofacial reconstruction database project (2002 Intensified Research Prioritised Area (IRPA), Eighth Malaysian Plan research grant), and the School of Surveying, University of Otago.

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Table 4. Results of the case study. Note that the distance calculated from the triangulation method was selected as a 'gold

From point	To point	Caliper vs. triangulation (mm)	Natural point method vs. triangulation (mm)	Control frame method vs. triangulation (mm)
2	4	0.11	1.36	3.57
3	6	0.03	0.77	1.61
6	13	0.56	2.01	1 .87
16	17	1.60	0.20	0.81
1	5	0.30	0.70	7.64
7	8	0.66	2.00	1.67
10	11	0.63	0.66	2.87
4	14	1.09	1.10	3 .56
2	12	0.31	0.15	1 .44
Statistics	*Mean*	***0.59***	***0.99***	***2.78***
	Variance	***0.22***	***0.42***	***3.77***
	Std Dev	***0.50***	***0.65***	***1.94***

DAVID GOODWIN

PhD Student, School of Surveying
University of Otago
e-mail: goodwind@albers.otago.ac.nz

Dealing with priceless treasure: comparing land with customary links

ABSTRACT

Informal land tenure rules may be important in supplementing formal land rules. This is perhaps especially true where features of customary tenure have survived to the present day. Beginning with an historical comparison, this paper goes on to describe work in progress on a research project that sets out to compare informal tenure rules over Maori freehold land in New Zealand and the Communal Areas of Zimbabwe, and how and why these are changing.

DAVID GOODWIN is Zimbabwean born. He completed BSc (Hons) at the University of Cape Town 1982, registered as a surveyor then lectured at University of Zimbabwe 1986-2003. During that time he took up a Commonwealth scholarship for an MSc in England. He emigrated to New Zealand in 2003, before taking up a PhD scholarship with the University of Otago in February 2004.

INTRODUCTION

Approximately 6% of land in New Zealand and 42% of land in Zimbabwe falls outside of the 'Western' tenure present in the rest of the country. This land, namely the Communal Areas of Zimbabwe and Maori land in New Zealand, has retained features of customary tenure, such as the principle that land can be used but not owned outright. In both cases, land is perceived as having a value that goes beyond money. Maori land in New Zealand is called a *taonga tuko iho*, a 'priceless treasure', 'of special significance to Maori people'[1], while Communal Area land is still called *musha* or *khaya* even by many urbanites, meaning 'home'. In other words, not where it is expedient to live on account of employment or for any other reason, but where a person feels they truly belong. This land is increasingly subject to formal (codified) rules, but informal rules still play a part. Such rules are important. North tells us that formal transformation of a society 'cannot be completely understood without exploring the survival and persistence of many informal constraints'. However, he warns that they may defy neat definition and be difficult to test.[2] This paper describes work in progress on a research project that sets out to compare informal tenure rules in the two countries, and how and why these are changing.

The paper is an interim report only. It looks at the comparison countries under three headings:

- A brief history of land, side by side, because present actions can only be fully understood with reference to the past.
- Formal rules used in administering the

land.

- A summary of initial interviews on the Maori side of the research project up to June 2005 (this represents approximately half of the Maori interviews planned). The Zimbabwean fieldwork, completed between July and September 2005, will be reviewed not here but in a later paper.

AN HISTORICAL COMPARISON

The histories of Zimbabwe and New Zealand run remarkably parallel and yet it is of interest that these histories have spawned contrasting tenure forms over residual aboriginal lands. In New Zealand, a type of qualified freehold prevails while in Zimbabwe's communal areas we see a modified form of customary tenure. Some of the causes for this divergence doubtless have their roots in historical causes and a brief historical summary follows to provide context for the comparison:

It can be seen that, allowing for an offset

Zimbabwe	New Zealand
Earliest inhabitants possibly the San. Later, the Bantu tribes we now collectively call the Shona.[3] Still later, the Ndebele (Amandebele/ Matabele).	First Maori landings from Polynesia not certain but perhaps in the 1200s.[4]
Early visitors from Europe included: Explorers & Missionaries Hunters (large land mammals) Traders (e.g. gold, ivory) - Guns, pots and blankets were important in trade (Guns were not just desirable but necessary for preserving a military edge, e.g. the Matabele defeat by better armed Batswana in 1885).[5] 1838, Matabele occupy SW Zimbabwe & partially subjugate Shona tribes. Inter-tribal raids exacted tributes of cattle, crops, women & slaves. Conflict used as a justification for 'civilisation' of natives. Treaties, concessions etc	Early visitors from Europe included: Explorers & Missionaries Hunters (whales and seals) Traders (e.g. flax and timber) - Guns, pots and blankets were important in trade (Guns were not just desirable but necessary for preserving *mana*[6] and a military edge in the Musket Wars).[7]
	Inter-tribal conflict not uncommon (e.g. the "Musket Wars" before 1840) Conflict used as a justification for 'civilisation' of natives.
e.g. 1870 Tati Concession (mining only, small area) 1880s: The scramble for Africa 1887 Treaty of friendship/alliance with Boers[8] 1888 Moffat Concession with Britain (no concessions without British sanction) 1888 The Rudd Concession (mining rights) 1891 Lippert Concession (to deal in land). 1889 British South Africa Company Charter.[10]	1831 Letter from NZ chiefs to King William IV noting French threat and asking for friendship and guardianship 1835 Declaration of Independence but also confirming a desire for Britain's protection 1838 Formation of the NZ Company 1840 Treaty of Waitangi/Tiriti o Waitangi (the Maori version, signed by different signatories).[9]
Discontent and rebellion	1840 New Zealand Company Charter.
1893 partial conquest of the Matabele 1896-7 Ndebele and Shona uprisings, concluded in a conditional surrender.[11] Some concessions/sales were over disputed land, perhaps to bolster	Discontent and rebellion 1860s New Zealand wars Partial conquest of Maori
Lobengula's possession claims[12] Some dishonourable land dealings and labour practices balanced	At least some concessions/sales were over disputed land, perhaps to bolster possession claims[13]

against selfless development work and a genuine desire (a) to improve the lot of native tribes and (b) to reduce crowding and ameliorate squalor in Britain.	Some dishonourable land dealings and labour practices balanced against selfless development work and a genuine desire (a) to improve the lot of the Maori and (b) to reduce crowding and ameliorate squalor in Britain.
Legal system borrowed from the Cape of Good Hope as at 10 June 1891. Roman Dutch law.	Legal system borrowed from New South Wales as at 21 May 1840. English Common law.
External controls of Privy Council and a notion of ideal justice in the form of the "Crown".	External controls of Privy Council and a notion of ideal justice in the form of the Crown.
Entrepreneurial personalities drove Company interests e.g. Cecil Rhodes, fiercely patriotic (to Britain), not above 'squaring' people to achieve his ends but with a genuine desire for a Pax Britannia and equal rights for all civilised people.'[14]	Entrepreneurial personalities drove Company interests e.g. Edward Gribbon Wakefield, 1816 eloped with a 16 year old heiress and probably resorted to forgery and perjury. In 1826 abducted and married a 15 year old from a wealthy family. Lucky to escape hanging. In Newgate prison espoused colonisation financed by land sales[15]

Differences

Zimbabwe	New Zealand
There will probably always be debate over the real extent of Lobengula's suzerainty[16], but the fact that he claimed the territory up to the Zambezi simplified negotiations enormously for those who chose to believe his claim.	New Zealand was not under a single *upoko ariki* (head chief) and the Treaty of Waitangi was therefore a far broader-based treaty than the Zimbabwe concessions.
No pre-emption reserved by the Crown and consequently more scope for the Chartered Company to allocate land at whim.[17] Some ill-considered land grants and an emerging problem of absentee landlords and 'farmers' who were only rent collectors.	Pre-emption by the Crown was enshrined in the Treaty of Waitangi but loss of land was nonetheless comparable with Zimbabwe. It may be significant that, no matter how extortionate the terms, the majority of land was purchased rather than stolen outright. Whatever the case, "two-thirds of the country, including virtually the whole of the South Island, had passed out of Maori ownership by 1862".[18] In 1865 the Native Lands Act abolished pre-emption and made sale even easier.
Native land technically had Crown Land status (today vested in the President) after a Privy council ruling of 1918. Effectively administered as customary land under Native Commissioners.	Native Land Court (later Maori Land Court) facilitated conversion of Maori communal title to individual title (Maori freehold title).[19]
Exponential growth of native population ensued when health was improved and famine and warfare reduced.	Early decline of Maori numbers (from European diseases and other factors) until after about 1900. Today, Maori population is increasing the most rapidly per capita.

A 'Fast forward' to the 1970s and beyond

Zimbabwe	New Zealand
1970s Extra-legal action in the form of a guerrilla war to redress land imbalance and past wrongs 1980s, Independence, Lancaster House Agreement & resettlement partially funded by Britain.2000s Land grabbing, increasing patronage of ruling elite, Fast-track land reform.	1970s Land march, occupations (e.g. Bastion Point), Waitangi Tribunal set up to investigate treaty breaches. This entailed a legal process culminating, for successful claims, in an apology, cultural redress (incl. name changes and conservation areas created) and economic redress (land and/or money) e.g. $170 million for Ngai Tahu settlement 1998 (now many times higher through astute investment).
1980 Independence Early 1980s, *Gukurahundi* (otherwise known as the 5 Brigade Massacres/'ethnic cleansing')	Circa 1980s, resurgence of *tikanga Maori* (Maori culture) *Te Reo* (the Maori language) etc.
1994 Land Tenure ("Rukuni") Commission	1993 Te Ture Whenua Maori Land Act
Tribalism still a factor[20]	*Iwi* (tribes) still a factor in decision making.
Issues today: loss of investment through diminishing security of tenure, agricultural land allocated to non-farmers with consequent loss of production, critically high inflation and unemployment, collapse of the judiciary, politicisation of food distribution, *murambatsvina* (clean up rubbish) campaign. starvation and unrest. AIDS/HIV deaths, orphans.	Issues today: Control of the Foreshore and Seabed, a constitution and possible Republic (this would supplant the idea of Crown). A criticism that elected Government have imposed undemocratic change without a referendum.*Hikoi* (protest marches) but the principle of legal redress appears strongly entrenchedMaori society disproportionately affected by violence & crime.[21]

in time of about fifty years, the two stories are not dissimilar. This poses a number of interesting questions. What factors have led to the divergence in tenure evolution path towards qualified freehold on the one hand and modified custom on the other? Can the two societies learn any lessons from one another? Are people making similar changes in land holding rules today and, if so, what are these and why? Would it be true to say that New Zealand (after the 1860s) has adopted mainly legal avenues to redress colonial wrongs and Zimbabwe extra-legal, and if so why?

FORMAL LAND RULES

After independence in 1980 in Zimbabwe[22], two pieces of legislation altered the administration of the Communal Areas (CAs). The first was the Communal Land Act (No. 20 of 1982), which superseded the 1979 Tribal Trust Land Act. The 1982 Act stipulated that land occupation and use of Communal Land should be by the consent of rural district councils, but otherwise the previous Act was little changed. Significantly, allocation of land was still required to be done 'with regard to customary law relating to the allocation, occupation and use of land'[23]. Secondly, a Prime Minister's directive in 1984 set up Village Development Committees (VIDCOs) and Ward Development Committees (WADCOs) to carry out grass roots administration. An acid test of this legislation occurred in 1994, when a Land Tenure Commission investigated rural land holding.[24] Overlapping interests were found between local government and traditional leadership and a desire noted among CA right holders to reinvest the latter with some of the power lost after Independence.[25]

Other legislation influenced the CAs indirectly. Overcrowding, a perennial concern, was given limited and localised relief during the 1980s when some right holders were assigned the use of resettlement land. However, by 1998 only about 70 000 families had been resettled, well below target.[26] Furthermore, rights to resettlement land were held by indeterminate permit only. This meant that, because of perceived insecurity and other factors, rights to CA land were usually retained by resettlement farmers despite a requirement to relinquish them.[27] Again, limited relief to overcrowding was promised by the post

2000 land invasions, but Spierenburg notes that the invaders have since had to make way for members of the ruling party and their allies and she questions whether 'the government of Zimbabwe ever intended to solve the land issue in favour of the land-hungry peasants in the Communal Areas'.[28] Latterly (mid 2005) some observers have called the *murambatsvina* campaign[29] a Pol Pot style depopulation of the cities to remove the maximum number of urban dwellers possible to the rural areas where they are easier to control[30]. However, difficulties have already been experienced in reintegrating urban dwellers back into traditional settings.[31]

In summary, then, what we are looking at in the CAs is a land area of almost half the country which has remained relatively unchanged during the political storms of the past forty odd years.

Turning to New Zealand, Te Ture Whenua Maori Land Act (TTWMLA) is the most significant legislation governing Maori land today. Its enactment followed a revival of *tikanga Maori*[32] in the last decades of the twentieth century when Maori spoke out increasingly stridently against historical injustices. In 1972 NZ Labour came into power and, for the first time in forty years, a Maori became Minister of Maori affairs.[33] In 1975 the Waitangi Tribunal was set up to investigate breaches of the Treaty of Waitangi. The 1970s saw various protest marches and actions, for example in 1976 (at the height of the guerrilla war in Zimbabwe) a famous protest action began at Bastion Point when the Crown announced plans to develop the Point, which had been taken in the nineteenth century under the Public Works Act to build a fort. When Bastion Point was no longer needed for defence it had not been returned to the Ngati Whatua *Iwi*[34] but given to the Auckland City Council instead and, at the time of the protest, was earmarked for subdivision.[35] Some of the *hapu*[36] occupied Bastion Point for seventeen months in protest until evicted in 1978 by a large force of police and army.

In 1993 TTWMLA was signed into law. A stated intention of this Act is 'to promote the retention of Maori land in the hands of its owners ...'[37] This being the case, it may only be sold or leased to a preferred class of alienees (essentially *whanau*[38] then *hapu* and then wider *iwi*).[39] Maori land is consequently relatively safe from alienation. However, today it faces certain challenges not faced by general land. For example, Grant writes that 'Maori freehold land is more likely than any other private land not to be actively managed.'[40] The reasons for this are complex, among them being widespread multiple ownership, which may compromise effective decision-making. Maori freehold land (MFL) has an average of 62 owners per title and an average of 425 owners in the highest ten percent of titles.[41] One contributory factor to this state of affairs is that the usual inheritance pattern for MFL leaves equal shares in land to all offspring. Trusts and incorporations work against this by enabling management to be concentrated in the hands of only a few trustees. In effect, incorporations and trusts such as the Ahu Whenua trust and Whanau trust can result in better use and administration of land.[42] However, rules for intestate succession, and the default status of the land as tenancy in common, ensure that the number of right holders will proliferate automatically unless specific action is taken to bequeath interests only to certain offspring. This is seldom done in practice. There is a reluctance to deprive any descendents of *turangawaewae*, literally a standing place for the feet, which is assured if a person has rights to even a symbolic 'thumbnail' of land. Other factors come into the *turangawaewae* equation as well, such as birthplace and both burial and birth locations of ancestors, making *whakapapa* (genealogy or descent) a key consideration as well. Many interviewees stated that the main issue at stake in owning a share in Maori land was *turangawaewae*, and the fact that MFL does not normally generate high revenues was immaterial. However, other factors cannot be ignored, including, perhaps, a hope that land might increase in value[43].

Apart from TTWMLA, other formal legislation governing tenure includes local planning legislation, for example Papakainga zoning where more than one dwelling may be built on Maori land with multiple-ownership, albeit subject to certain conditions.[44]

INITIAL MAORI INTERVIEWS

The project will try to document informal rules existing over Maori freehold land, and how these rules are changing and why.

Hopefully this might help us to:

- See what are perceived by right holders as key elements in land holding today
- Identify what changes are seen as desirable, viable and acceptable to contemporary local culture
- Understand reasons for the above in the light of an historical tenure evolution path and other factors
- Understand what factors, perhaps unwritten, work against change.

Methods and scope of the project

At the planning stage of every project certain boundaries need to be defined both geographically and regarding the extent of the topic area. These boundaries impose constraints and biases about which we need to be aware. For New Zealand, this particular project excludes foreshore and seabed issues and high country leases. In Zimbabwe it excludes 'fast track' land acquisition and resettlement. In the respective countries these topics are relatively new, emotive and politically sensitive. Geographically, only Ngai Tahu land is considered (occupying very approximately the lower three quarters of South Island, New Zealand), and only Ngai Tahu have been interviewed. Also, only Maori freehold land is studied not the very small remaining percentage of Maori customary land. In Zimbabwe, only the Communal Areas are considered (both in Mashonaland and Matabeleland), and large and small scale commercial farms and urban areas have been excluded.

Creating such boundaries invariably involves tradeoffs. By setting out to compare two countries, this project inevitably tends towards breadth at the expense of in-depth quantitative analysis of narrow topic areas. On the other hand, a broad canvas can sometimes make it easier to see patterns.

Interviews have been chosen to collect primary data rather than questionnaires, for a number of reasons:

i. There is a strong verbal tradition in both the Maori and Shona and Ndebele cultures and it is felt that respondents will feel more comfortable with this vehicle.

ii. Open-ended questions would seem to be more culturally sensitive in allowing respondents to have a say in steering topics and/or choosing not to divulge certain information, and allowing the interviewer to judge whether, for example, specifics on location and aspects of culture are sensitive and should be suppressed.

iii. Informal tenure modification is not well documented in the literature and conversations may proceed in unexpected directions. Interviews are expected to give more flexibility for information to be volunteered than would a predetermined questionnaire.

Verbatim quotations are sometimes included in this paper but confidentiality was promised to interviewees and no names are given, nor dates other than the year.

A good mix of interviewees has been sought, but already the potential for biased samples has been underlined. Several Maori spoken to said they were unable to agree to an interview in their personal capacity and would feel more comfortable if nominated by their *runanga*.[45] Proceeding by this route, *runanaga* not unexpectedly favoured *kaumatua*, mature men and women of good standing. It would be surprising if such people agreed on every point with the young and disenfranchised.

Provisional findings

It should perhaps again be stressed that this paper gives provisional findings only, stemming from Maori interviews up to the end of June 2005 (probably about halfway). To date, informal agreements have been found to include the following kinds of arrangement:[46]

- Unwritten leases/loans, either for rent or else just to pay rates and"keep the place tidy" or "keep the gorse down".
- Timeshare holiday home schemes for multiple right holders, or just arrangements within the whanau about camping.
- Parking understandings for church and *marae*.[47]
- Pedestrian access to *urupa*[48] over both *whanau* land and general land.
- Unofficial road access over land.
- *Whanau* land made available for weddings and *tangihanga*[49] etc on request.
- Give-and-take fencing agreements for a variety of reasons.
- New land-related tradition (such as weddings on the beach).
- Habitation rights augmenting a trust whereby individuals are permitted to stay on land and own what they build but can gain no rights in the land itself for selves or offspring.
- Private arrangements about which co-owners will live where on a block of land (e.g. an agreement between brothers).
- Informal zoning by a *runanga* to say e.g. that customary flax working is acceptable in one area of a reserve but that a large scale commercial enterprise will not be tolerated in that same area.
- Arrangements between those who have left and those who remain behind and exercise *ahi ka*[50] to care for *urupa* and send regular information.
- *Whanau* land made available for burying the placenta/*whenua*[51] of infants and stillbirths.

DISCUSSION

(i) An obvious question is whether tangible interests in land have, over time, tended to become divorced from intangible, and whether right holders are moving towards recognising this formally. In other words, perhaps at one time in the past the intangible benefits emanating from land (such as social cohesion and the security of extended family) might have been inseparable in a person's mind from the "goodies" that land provided (such as food and raw materials). But, if land ceases to be the source of livelihood, we might expect such a direct connection to be eroded or transferred. Today food and clothing might come from wage employment, via the supermarket, rather than directly from the land. Intangible benefits could as well come from government institutions (e.g. state social security, pension schemes), heterogeneous groups with no blood ties (e.g. neighbourhood, urban *marae*, church, social club) and a variety of localities (e.g. local or distributed urban neighbourhoods). It seemed significant that some interviewees had given thought to effecting a formal separation of symbolic and beneficial interests in land, for example by retaining rights to a square metre of land (*turangawaewae* would be preserved no matter how small) and freeing up the rest of the land for more intensive management under a single lessee or owner. No working examples of this have been found to date, but perhaps such a thing has already taken place. If not, it begs the question of what factors might have inhibited it. This avenue will be pursued in the remainder of the interviews.

(ii) Interviews seem to point to the possibility of a changing emphasis on what exactly constitutes *turangawaewae*, the secure foothold to land and belonging. In the past, forebears would normally have been buried on the same land that the family lived on and worked, even seasonally. New additions to the *whanau* would have had their placenta/*whenua* buried on the same land. *Turangawaewae* had its locus somewhere in a complex mix of productive land, burial of the *whenua*, the resting place of ancestors, memories and the sense of belonging to a tight-knit group. But it is a comparatively common recent phenomenon for, say, an urban dweller to have rights to fifteen pieces of land[52] scattered around the South Island most of which s/he has never seen, with various grandparents buried in still other locations and perhaps with a stronger sense of community with the neighbours over a city fence than with *whanau* who exercise *ahi ka* on the ancestral land. We might perhaps expect some confusion about what exactly constitutes *turangawaewae* and this has in fact proven to be the case. At the one extreme it is seen as being allied most strongly to burial places of the dead[53] and on the other to land rights held by the living.[54] Somewhere in between there lie the aspects of community, *whakapapa* and belonging.[55] Interesting questions are raised. For example, if a community moves locality yet somehow preserves its cohesion and identity, can we argue that the root of identity has come to reside more in a social or ancestral bond than in a connection with specific land? Is the original land ever visited or spoken about? And what happens if people have lived with the security of knowing that a family home will have to take them in if they have to ask but, when it comes to the crunch, this hope proves ill-founded? This has certainly been the case following recent events in Zimbabwe. People who have lived in the conviction that their real "home" was in the CAs have today had this tested and found that for one reason or another they are not welcome.[56]

(iii) Ballard offers the view that urban Huli in Papua New Guinea remain Huli particularly through reference to those who remain on the land[57] and it would seem to be important to ask how true this is of urban Maori, Shona, Ndebele and how in practice, links with family land are kept alive. For the diaspora who have retained interests in customary land in New Zealand and Zimbabwe societies, certain issues seem to be emerging as important, including:

- Rights and duties associated with staying behind on the land (*ahi ka* in NZ) including the care of graveyards/*urupa*.
- *Mana* for distributed communities[58]
- Communication links (practical issues involved in 'keeping in touch').
- Flow of resources and knowledge to and from city and country

(iv) There appears to be a fairly solid body of opinion supporting retention of Maori freehold land within family and tribal groupings. This position is not seen as conflicting with entrepreneurial interests over general land (e.g. 'That side of the fence [general land] I buy and sell land, this side [MFL], no'[59]). However, there are dissenting voices. Changing the status to general land will normally increase the land's value, after which one suggestion is that it could be sold in order to pay off mortgages and generally help the younger generation contend with the new urban realities they face. This divergence of opinion can create tension.

(v) Initial evidence seems to suggest that localised, family-specific cultures may modify prevailing norms and be significant in longer term landholding and trends. For instance, interviews have flagged as important that, if for example a grandparent believes strongly in buying land rather than selling it and will make personal sacrifices to achieve this, then even if such a practice runs counter to the norm the same propensity can often be traced down through successive generations.[60] The same thing may be true of such things as a belief in quality education whatever the cost, or in inculcating a work ethic. This can result in a correlation between informal actions taken within families which are at odds with practices within other families.

(vi) Changes in informal rules with time may reflect wider trends in industrialisation and demographics.[61]

(vii) Rumbles writes:

'Because legal action and social action are tightly intertwined within small-scale stateless societies, sometimes legal process as a social activity, is more important than the actual outcome.'[62] Maori customary law has to a large extent been supplanted by statute, and legal process often takes place in the Maori Land Court rather than on the *marae*. It has to be to be asked, therefore, if the role of the *marae* and criteria for speaking on the *marae* have altered accordingly.

(viii) Some explanations given in interviews drew on illustrations from the distant rather than recent past and suggested that the roots of some perceptions about landholding today have persisted from a time even before nomadism or seasonal migration gave way to more settled agriculture. For example, from Maori tradition we have the *waka iwi*[63] practice of travelling with ancestral bones and a tradition of naming that spoke of seasonal migration (for example, "that's where you always stayed on your journey to the lakes"[64]). It is unclear at this stage whether such knowledge colours informal land rules today.

(ix) Other important issues may include boundaries (of land and land rights), boundary records (written or verbal), naming of boundary features, *waka waka* marks[65], totemism, exclusivity of rights[66] and CBNRM.[67]

CONCLUDING REMARKS

This research is only part way through. If this paper has any merit it is perhaps in the juxtaposition of the histories of the two countries from the point of view of land, and an early attempt at synthesising informal tenure modifications over Maori freehold land.

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1 [TTWMLA, 1993: Preamble]

2 [North, 1990:36]

3 [Beach 1994, 1 ff]

4 [King, 2003:51]

5 [Glass, 1968:4] & [Blake, 1977:45]: "Armed with modern rifles, they destroyed the Ndebele army near the Okovongo River."

6 standing, or authority

7 [King, 2003:132]

8 e.g. [Blake, 1977:38]

9 [Christchurch library (Treaty of Waitangi)]

10 e.g. [Lander, 1992:1]

11 [Blake, 1977:136-144]: The great indabas in the Matopo hills.

12 [Warhurst, 1973:56] suggests that Lobengula granted a mining concession in the Tati area because it was disputed territory between himself and Chief Kgama, to secure his borderlands. Other accounts point to a similar ploy being used elsewhere.

13 [Ballara 1982:539] cites, e.g. Te Rangihiroa, 1911: "Where Maoris have had an insecure tenure they have been only too anxious to sell."

14 e.g. [Blake, 1977:35]

15 e.g. [Grant, 2003] & [Christchurch Library (Wakefield)]

16 e.g. [Lloyd, 1992:125], [Warhurst, 1973:124,125], [Howman, 1977:2,3]

17 e.g. the Victoria agreement [Glass, 1968:149-151]

18 [Boast, 2004:66]

19 [Gilling, 1994:135]

20 [Unendoro, 2005] found that the ruling party is overwhelmingly represented by Zezuru, which is the president's tribe and not even the most numerous in the country.

21 [Scott, 2005]

22 From 11th November 1965, when UDI was declared (Unilateral declaration of Independence), Rhodesia (as Zimbabwe was then known) considered herself independent. However, to Britain she was still a colony.

23 [Zimbabwe Government, 1982: s.8 (1)&(2)]

24 [Rukuni, 1994] (Sometimes referred to as the "Rukuni Commission")

[25] [Torhonen and Goodwin, 1998:97]

[26] [Spierenburg, 2005:199]

[27] [Interviews, 1996 & 2005]

[28] [Spierenburg, 2005:197,198]

[29] literally "drive out trash".

[30] [Lamb, 2005]

[31] e.g. [IRIN (UN), 2005]: "Those with money have left for villages but many have no family to go to and the country's fuel shortage means buses are few and far between. Others have returned to Harare, claiming village chiefs are refusing to accept them because there is not enough food." Also [Lamb, 2005]

[32] Maori custom

[33] [Evison, 1993:486]

[34] Tribe

[35] [Durie, 1998:124,125]

[36] Tribal sub-grouping

[37] [TTWMLA, 1993:Preamble]

[38] Family (pr. "far know")

[39] [TTWMLA, 1993: s4]

[40] [Grant, 2000: s9]

[41] [Grant, 2000: s9]

[42] [Maori Land Court (Trusts), 2002] & [Maori Land Court (Incorporations), 2002]

[43] e.g. the South Island Landless Natives Act 1906 land which was typically remote and difficult to access but which today has increased dramatically in value owing to the 24 000 hectares of indigenous forest concentrated on just over 50 000 hectares of SILNA land [Ministry of Agriculture and Forestry, 2005]

[44] e.g. [Banks Peninsula District Council, 2002:164]

[45] Maori council

[46] [Interviews, 2005]

[47] Open space in front of a meeting hall. Used loosely to refer to the hall itself.

[48] cemetery or cemeteries

[49] mourning ceremonies

[50] lit. "keeping the fires burning"

[51] *Whenua* in the Maori language means both "land" and "placenta".

[52] [Interviews, 2005]

[53] [Interviews, 2005]: "To me your urupa is really your *turangawaewae*"

[54] *Turangawaewae* is connected with land rights and ancestry: "you can sit there in full confidence that not only do I *whakapapa* here I have landholding … even if it's … so small [gesture of finger and thumb about a centimetre apart]

"[55] [Interviews, 2005]: "A sense of belonging … That is really my core. … everyone, practically everyone knew me. They knew my father." There (your ancestral home), people "knew you when you didn't know yourself."

[56] (cf. earlier footnote): Some people have returned to Harare, claiming village chiefs are refusing to accept them because there is not enough food.

[57] [Ballard, 1997:50]

[58] In addition to whakakapapa "appropriate skills of mana tangata" [i.e. personal leadership qualities and acumen] need to be demonstrated. [Law Commission, 2001: s141] How is this achieved in practice for distributed communities today?

[59] [Interviews, 2005]

[60] [Interviews, 2005]

[61] cf. [Boserup, 1965]

[62] [Rumbles, 2005:2] cites [Keesing & Strathern, 1998].

[63] [Interviews, 2005]: "The body would be buried for a certain time and then they would lift the body, scrape the bones, and put them into a *waka iwi* [literally "canoe of the tribe"] and because they were a nomadic people they carried their *waka iwi* around with them."

[64] [Interviews, 2005]

[65] [Interviews, 2005]: Natural marks ("by this tree, by that rock, by this creek, by that hill, that's your area there") pointed out to families or extended families giving occupational or hunting rights.

[66] [te Velde, 2004] Personal correspondence and [Dore, 2004]

[67] Community Based Natural Resource Management

MICK STRACK

School of Surveying
mick.strack@otago.ac.nz

Back to the land: Walking access to the outdoors

ABSTRACT

New Zealanders enjoy their open, green, forested and mountainous country and understandably want to ensure that their access to the land and waters is enhanced. There are various mechanisms and opportunities to extend publicly accessible land. The Walkways Act under the authority of a dedicated access agency could provide for much of what we need. But access should not be open and unfettered; the productive capacity of the land and conservation needs must be protected. Education and promotion of a Countryside Code should allow all users to cooperate and be satisfied. This paper sets out some of the opportunities for improved access to our countryside.

MICK STRACK's primary lecturing focus is in Land Tenure Studies at the School of Surveying. His research revolves around property rights in land, rivers and the sea; indigenous and customary rights; Maori land issues; and rural and urban sustainability. He is an enthusiastic user of New Zealand's open space.

New Zealanders are now overwhelmingly part of an urban society, but we retain a rural and open-space ethic.[1] We like to think that we can always get out into nature for some exploration and recreation, and we want to ensure that there is adequate land set aside for public use. Issues to do with access to land have been at the forefront of public debate in the last few years; the foreshore and seabed, the Queen's Chain, High Country Tenure Review, government purchases of additional lands for the conservation estate, and access reports and submissions. [2] The access debate has been promoted amongst lobby groups, academics, politicians, policy makers, and special interest groups, and it appears the general public response has been to demand the extension of the provisions for setting aside land for public use. The rhetoric is premised on the perception that access is being restricted. But when one examines the reality, it is far from clear that the general public is unreasonably deprived of access to land or water.

There is no doubt that with a growing urban population, and with the population's declining connections to natural and rural New Zealand, the requirements for more and better access to the open lands of our beautiful country must increase. A very large proportion of New Zealand is public land, but a large proportion of this is mountain, high country and bush land. Urban New Zealanders need more access to rural and pastoral land in closer proximity to our urban centres. Not only do most New Zealanders picture themselves as outdoorsy people, we also have a close affinity with water; the sea, rivers and lakes, primarily for recreational boating and fishing, so access to the water is especially important.

THE FORESHORE AND SEABED

In 2004, amidst much controversy, the government passed the Foreshore and Seabed Act. The controversy arose from the Act being initiated to divert the common law legal process of the investigation of the possibility of a Maori customary title to the foreshore and seabed. In 2003, the Court of

Appeal made a decision[3] that acknowledged that Maori customary title had not necessarily been extinguished, and that the Maori Land Court was the appropriate forum to determine whether or where it existed. The government and a significant sector of the public misinterpreted this decision as if Maori would be able to take freehold title to the beaches and exclude the public from free and open access. As I have argued elsewhere,[4] it was well within the capacity of the government and the law to ensure that any customary rights would not override public access to the foreshore and seabed, and certainly not to the beaches. However, the subsequent legislation served to alienate Maori not just from their foreshore and seabed, but also from their common law rights to access the courts. The government took the view that the only way to provide certainty about public access rights was to vest all the foreshore and seabed in Crown title. In other words, only Crown ownership, not the common law, is capable of protecting public rights.

THE QUEEN'S CHAIN

The access to land debate in New Zealand usually starts with the concept of the Queen's Chain; the idea that there should be public access to the banks of all our water bodies.[5] This is an easy rallying point for lobby groups and a concept that the public can grasp unquestioningly. But it is important to question this concept and our focus on it. We certainly want more and better access to our open countryside, but perhaps riverbank access is not the type of access that we should be demanding.

What is the origin of this thing we call the Queen's Chain? Queen Victoria's instructions to Governor Hobson in December 1840[6] were quite extensive, and included all manner of instructions about the administration of a new colony. Many of the instructions turned out to be rather inappropriate for this newly colonised country and were not implemented. For example, the system suggested for the subdivision of land parcels (a division of the land into rectangular counties of 40 miles square[7]) was unworkable in New Zealand's varied topography. And to pick another example almost at random – the government was not allowed to raise money by lottery – clearly not enforced now.

The instruction applying to what has since been referred to as the Queen's Chain,[8] has regularly been deconstructed and quoted out of context to support an argument for the requirement to establish a complete network of waterfront reserves for public access. The instruction is almost buried in a list of other land allocation matters which suggests that land should be set aside (i.e. reserved for public purposes) for a multitude of purposes including roads, schools, churches, recreation reserves, or for 'sites of quays or landing-places which it may at any future time be expedient to erect, form, or establish on the sea coast or in the neighbourhood of navigable streams,' or for any other purpose of public convenience. It further requests that surveyors define such lands on plans, and that the government may not dispose of any such lands or allow them to be occupied by any private person for a private purpose. The instructions say nothing about a general reservation of lands along the banks of all watercourses nor that there should be free and open public access to all water bodies. Notwithstanding that, many early surveyors saw fit to provide for river bank reserves, separating private parcels from the water. These reserves were often in the form of legal roads, albeit with no intention that they would be formed as roads. Such a designation was primarily a matter of convenience although from a legal point of view, it suggested the land was provided for access rather than set aside for conservation (i.e. designated as a reserve).

So there has been something of a tradition that (at least Crown-owned) lands adjoining rivers, lakes and the sea have often been provided with some sort of publicly reserved strip and many of our rivers and lakes do have good coverage of riparian reserve land.[9] The problem is that many do not have such strips, and even if they do it is almost impossible to observe on the ground whether a public strip exists. To find out that information requires time and some expertise in searching the land records[10] and referencing such records to actual locations. There are no easily accessible maps to record for public information, the extent of accessible land or the extent of the public rights.

CURRENT LEGISLATIVE PROVISIONS FOR RIPARIAN ACCESS

The Crown has implemented a series of legislative means by which additional riparian reserves may be set aside, and the definition of where the strips may be and the legal status of such strips is many and varied.[11]

The current legislation covering the setting aside of these riparian strips includes the Conservation Law Reform Act 1990 and the Resource Management Act 1991. The Conservation Law Reform Act provides for a 20m riparian strip to be set aside upon the sale or lease of any Crown land. The RMA provides for the setting aside of an esplanade reserve or strip upon the subdivision of land into parcels less than 4ha adjoining a river (over 3m wide), lake (over 8ha in area), or the sea. This is effectively a taking – or confiscation of land by the Crown without compensation. Under normal rules of law such a taking is not allowed, however given that it is not strictly speaking compulsory (the subdivision of land being the choice of the landowner), the Crown has implemented the provision without too much resistance. The setting aside is essentially mandatory for subdivision of parcels less that 4ha, and dependent on a specific rule in a district plan for parcels over 4ha. So the large open rural parcels where you would expect access to be most desirable and extensive, is the very area where it has not been required under this legislation.

Section 229 of the RMA, stating the purpose of esplanade reserves or strips, indicates that they can be for one or more of the three purposes: conservation, access or recreation. This would suggest that a consent authority should be specific about which purposes any reserve or strip is set aside for. Furthermore, because the reserve is vested in and administered by the local authority, the expectation is that it should also be managed for that specific purpose. From a planning and management perspective, it would be more sensible for any requirement for an esplanade reserve to be stated in the district plan and only taken for an identified purpose over land which has been specifically identified. This means an esplanade reserve would only be taken when actually needed and justified by the local authority, not just taken for the sake of an arbitrary rule for no identified purpose as is the case now. Such a justification would make the confiscatory nature of this taking of esplanade reserve more palatable, but it would also ensure that the taken reserve would have a purpose and would address the needs of potential users.[12]

Esplanade reserves for access alongside the sea, lakes and rivers should only be taken when the specific need has been identified and when the local authority has prepared a management plan to cater for that need. Such a management plan for access would be expected to include appropriate mapping, high quality signage, public notification, public amenities like gates and stiles, and route clearance work. Clearly none of that is done when esplanade land is taken now.

The RMA and the CLRA provide an inadequate vehicle for increasing public access, only addressing access on riparian strips, and even that very imperfectly. The Queen's Chain only exists where it has been specifically surveyed and defined in our land records and can now only be added to when private land is subdivided or Crown land is alienated. Clearly not a good recipe for attaining total and assured coverage of access to all our waterways. But does that really matter?

RIPARIAN MANAGEMENT – BEST PRACTICE

To have open walking access along our riparian strips is destructive of the conservation values of such strips, almost certainly not the most appropriate walking route, and just not necessary. From an ecological point of view, river margins are extremely important as habitat and as transition zones between the water and the land, and indeed both the current legislative means for setting aside riparian reserves list conservation as the first purpose (followed by public access and recreation). Many rivers are suffering from degraded water quality due to pollution runoff and inappropriate management of the riparian zone. The conservation values of the riparian zone are vitally and increasingly important. The Department of Conservation and Landcare Groups are addressing habitat, runoff and bank management issues by encouraging the (re)planting of riparian zones. Vegetation restores habitats for aquatic life and birds, it acts as a filtration zone for all surface runoff, including soils and contaminants, and it protects the banks from erosion.[13] Many of the problems with effluent runoff from intensively grazed dairying pasture, could be mitigated by well vegetated riparian strips. Many of our wild rivers are well vegetated down to the river banks, just as parts of our coastline are. Best conservation management practices suggest that those areas not well vegetated should be rehabilitated; dune grasses restored, native species replanted, wilderness replenished. Open public access to the riparian zone, even just walking access, will clearly compromise that conservation management.

COUNTRYSIDE TRACKS

Most fishers are resourceful people and are able to scout out their favoured rivers and fishing spots, and have usually been able to gain access to rivers by right or by seeking consent of the land holders. Most enthusiastic trampers and mountaineers are similarly well catered for with access to open high country reserves and National Parks. Vast areas of New Zealand are part of the Crown's conservation estate – National Parks and scenic reserves – in theory open for access, but in practice (and as a matter of policy and good conservation goals) access is largely confined to tracks. Most users usually keep to fairly well established paths and marked routes, because that usually represents the easiest and most logical places to go, and it recognizes that public access adversely affects the ecology. We are no longer part of a pioneering society where it is necessary to bushwack our way through the vegetation to get from A to B. We need to protect our vegetation and our riparian zones, and predominantly stick to paths for our personal explorations of our environment.

Tracks near the sea or rivers can provide pleasant outlooks, but they do not need to be right on the bank or within 5m or 20m of the bank. Some of the most successful tracks pass by rivers, climb hills and saddles, traverse the bush, and provide variety generally focused on a river valley, lake view, or seascape, but only rarely traversing the close riparian zone. It is inappropriate and unnecessary to confine walking tracks to the river bank. Access should be negotiated to provide the most appropriate route; considerations of landscape and scenic variety, biodiversity, historic and cultural relevance, accessibility and user requirements, should determine route and location, not proximity to a water body.

HIGH COUNTRY TENURE REVIEW

Many of the South Island's pastoral leases, the iconic tussock sheep grazing lands of central Otago and Canterbury, are being renegotiated under the terms of the Crown Pastoral Land Act 1998 (CPLA). Pastoral leases under the Land Act 1948 provided for a pastoral lease of Crown land for a period of 33 years and with a perpetual right of renewal. Apart from significant limitations on land use, the lease provided the lessees with a very secure tenure, which is highly valued by the market. The leases also gave the lessees exclusive rights to the land and the protections of the laws of trespass. Public access into, across and through this land is not available as of right. However, many lessees allow public access on condition of gaining personal permission.[14]

The tenure review programme allows for lessees to negotiate with the Crown for the conversion of productive parts of the leasehold land to a freehold title, usually accompanied by the release of some of the other (perhaps ecologically sensitive) leased land into the conservation estate.

The purpose of this tenure review and title conversion is to 'promote the management of reviewable land in a way that is ecologically sustainable'[15] and to allow 'land capable of economic use to be freed from the management constraints resulting from its tenure.'[16] Further, the purpose is to protect significant inherent values by either creating easements, covenants or restoring the land to Crown ownership and control.[17] Subject to these purposes, the Act seeks to 'make easier – the securing of public access to and enjoyment'[18] of the land.

The land that reverts to Crown ownership and control under this Act is added to the conservation estate, and at least in theory becomes open to public access. The terms of the settlement should include the provision of direct and legally secure access to that land. This is often provided for by an easement over exiting farm tracks, or ensuring that the Crown land has direct frontage to a public road. There has not appeared to be any overt promotion of the accessibility of this newly acquired Crown land, and it appears that the priority is merely to acquire the land into the conservation estate. There has been little focus on a management plan for ecological management,[19] much less for promoting public access.[20]

THE CONSERVATION ESTATE

The Crown is buying huge areas of land to add to the conservation estate – for a continuous and extensive Conservation Park throughout the high country. The purchase of Birchwood Station (now known as Ahuriri Conservation Park) for what has been described as a premium price[21] – \$10m for 23,700ha – is illustrative of the value the government has chosen to put on inherent conservation values. The definition of Inherent Value in the CPLA includes the 'cultural, ecological, historical, recreational or scientific attributes or characteristic' of the land.[22] Subsequent to the purchase, there was much discussion about whose interests and whose access was being provided for in this purchase, and indeed in the wider concept of a conservation park. DoC made much of the fact that, 'the public status of the land means everyone is guaranteed the freedom to wander at will on foot, by mountain bike or on horse back.'[23] Other users, notably 4WD owners, have complained about their exclusion from access to most of the park,[24] but DoC mounts a relatively easy justification for maintaining its responsibilities for providing access only to non-motorised users.[25]

This huge investment in high country land is undoubtedly focused on maintaining ecological values in remote valleys and mountain land, but it is also portrayed as satisfying the demands for more public access. These additions to public land are indeed significant contributions to protected lands, they serve to link the South Island's national parks, nature and scenic reserves, forest parks and conservation parks with an integrated and continuous ecological focus. But they provide little for the urban dweller needing to reconnect with nature, to get the quick physical, psychological or spiritual revival of a walk in the countryside.

WALKWAYS ACT 1990

There are other mechanisms for the extension of public access to land and water. The Walkways Act provides for the establishment of public walkways through public and private lands. The potential under this Act is enormous and could be an excellent vehicle for the expansion of access opportunities for New Zealanders. However since the responsibilities under this Act were passed from the Walkways Commission to the Department of Conservation, progress on expansion of a walkways network has ground to a halt. This is hardly surprising; it is not in DoC's best interests to promote public access given that it often conflicts with conservation goals, and the department has no incentive to negotiate with private landowners for more access. A new Access Commission as has been recommended to the government,[26] could reignite progress to provide better public access to land. The walkways legislation is capable of providing for what is needed.

The purpose of the Act is stated[27] as providing walking tracks "so that the people of New Zealand shall have safe, unimpeded foot access to the countryside for the benefit of physical recreation as well as for the enjoyment of the outdoor environment and the natural and pastoral beauty and historic and cultural qualities of the areas they pass through." Significantly, in terms of the ongoing public debates, the Act specifically protects the rights of property owners, and ensures that the access rights created are for walking purposes only.[28] The RMA Tenth Schedule prohibition on the rights inherent in an esplanade strip are similar to the offences listed under the Walkways Act.[29] Although administered by a different authority, the access rights are very similar.

The Walkways Act provides for the controlling authority to identify land for access, to consult and negotiate with owners of that land, and to provide compensation for the assignment of rights. The creation and registration of an appropriate lease or easement over the land is required to record the public access interest. The authority has powers to mark out the walkway on the ground, to facilitate access onto the walkway, to promote the safe use of the walkway and to establish facilities and amenities to enhance use and convenience of the walkway.

The proactive implementation of this Act would serve to provide for more and better access to land. It could provide in a more direct and appropriate way, possibilities for outdoor access that are more meaningful to the public than the purchase of large areas of remote high country land.

PAPER ROADS

Legal roads are set aside, surveyed and identified on titles and plans to give allotments legal frontage. Many such roads were defined on plans with little thought of topography. They may not have been formed because they were never actually needed for physical access and because they may never have followed practical routes. They are usually occupied by surrounding owners as if part of their private property. These paper roads can legally be used for public access, although they are unlikely to follow useful routes and are difficult to locate on the ground. They could, however, be used for land exchanges when more appropriate routes may be available and arranged with land holders.

BARRIERS TO ACCESS

Surveying

In the past, certainty about rights has usually required a clear surveyed definition, Crown ownership and some compensation for land taken. The clear and unambiguous spatial definition of land parcels is the ideal upon which our property law is based. This usually means surveyors' pegs in the ground. The costs of surveys of tracks, easements and boundaries can impose a financial barrier to the development of more countryside tracks. Cadastral survey regulations and standards have been strictly adhered to in keeping with the law's emphasis on clear and distinct property rights. It would appear that such strict compliance is not really necessary for what could easily be promoted as a casual or informal establishment of relatively non-intrusive foot traffic. High levels of survey accuracy are redundant in such a situation when all that is really required could be a line showing a public walkway marked on an aerial photo'– a visual representation that is clear and simple enough for public recognition.

Just as some land boundaries may be defined by the ambulatory boundary of an adjoining watercourse, so too can strips of land be defined by reference to a bank, a ridge, a fence, a track and a set width beyond that feature. It is therefore possible to remove the impediments of intensive survey definition and high survey costs from the equation.

Property Rights

Property rights in land can be unbundled and redistributed. Crown ownership is not necessarily required, but title can remain with any private land owner while certain rights of access can be assigned to the public. Such reallocation of rights would naturally affect the title holder's otherwise unlimited rights, and should by definition be compensated. But given that the landowners may still be able to utilise the land for farming operations, the compensation need not be great.

While private property rights are generally very strongly protected in New Zealand law, the perceived threat to these rights from the government's recent proposal[30] to set aside a 5 metre riparian strip alongside all rural water bodies in lieu of a formally established esplanade reserve, caused very vocal objections from the farming lobby, and may have been behind a Bill introduced into parliament to provide even stronger protections of private property rights. The Bill of Rights (Private Property) Bill seeks to formalise the right to own property and the right to compensation in the event of deprivation of property.[31]

Farmer objections and the 2005 election focus prompted the government to step back from their proposal and once again established another committee[32] to review the issues involved with legislating for land takings.

The private property paradigm may be hard to shift, given that it is fundamental to the history of land settlement and land legislation in New Zealand. The alternative paradigm views land as having some public character and all land owners and land users (including all wanting access onto the land) having a sense of responsibility and duty towards the land and the people. Such an idea aligns with sustainability issues of environmental care, social equality, and land ethics.

Mapping

The problem with existing marginal and esplanade reserves, unformed paper roads, and even some established walking tracks is that their existence and extent is difficult to identify on the ground. Good mapping is what is required to facilitate the public's rights. Land Information NZ (LINZ) is the government agency that provides mapping services to the government, and that department's brief is to produce maps "to meet the needs of New Zealand Defence and Emergency Services."[33] They have no requirement to provide maps for public and recreational use. This is clearly a major barrier to confident public access to public lands in New Zealand.

New Zealand has a fine heritage of recorded land information; both cadastral and topographic. This information is public and should be available for the public in a readily accessible form. There are difficulties in identifying what is on the ground (e.g. the standard of pathways) and also what the legal status of tracks may be, but these are relatively minor issues dealt with in all mapping operations. The information and systems are there: it just needs government backing to provide public service mapping.

Conflicting users

The shift in recreational access behaviour from mainly walking to now include mountain bikes, trail bikes, 4WD vehicles, and even in the winter, cross country skiing, has opened up some conflicts between different users. Recreational vehicles need to be catered for somewhere, but public access lands should reasonably and sensibly focus on walking access only.

Coordination

Recent promotion of the access agenda has been guided by the Ministry for Agriculture and Forestry[34] apparently because it is an issue relating to rural land, but there would appear to be some conflict in roles here. MAF deal with agricultural policy, but is an unlikely place to get a public (and urban) perspective on rights to land.

The issue of access is one that affects all New Zealanders and deserves a dedicated commission to coordinate access arrangements. This paper gives some hints at the sort of work required of an access commission; identification of existing access rights; identification of proposed access tracks; negotiations with landowners, councils, recreational groups; assessment of compensation; construction; promotion; education; signage and mapping, etc.

COMPARISONS WITH ENGLAND

The New Zealand reports have drawn on the experience of European countries and how they provide for public access by custom and tradition or by legislation.[35] Several European countries have a general right to roam on unenclosed lands which usually includes forest land and alpine meadows, and many have well established network of access tracks.

England[36] has recently introduced new legislation to extend the right to roam over identified and mapped lands. The **Countryside and Rights of Way Act 2000 (CROW) provides for 'open access' to 940,000 hectares or about 7% of the country.**[37] The Ordnance Survey Explorer maps show all known access lands where there is a walking access right. This is separate from existing walking tracks, bridleways, and other public ways. Key components of the legislation are:1) to ensure that adequate maps are available to inform the public about the extent of this land; and 2) a Countryside Code is actively promoted.[38] The Countryside Code ensures that there is an emphasis on responsibilities, not just rights. The Countryside Code is clear and concise:

- Be safe – plan ahead and follow any signs
- Leave gates and property as you find them
- Protect plants and animals, and take your litter home
- Keep dogs under close control
- Consider other people.

The brevity of this code makes it easy to include on signage but it is further elaborated and explained in advertising leaflets. The government agency in England is well organised to provide signage, promote maps, educate the public, and advocate for the extension of access lands – a possible model for a proposed access agency in New Zealand.

COUNTRYSIDE CODE

Almost everyone is in agreement that a countryside code of conduct is an essential element of the formula to provide for the ongoing needs of access for New Zealanders. Many urban New Zealanders have little understanding of appropriate behaviour in rural New Zealand, both as to the special requirements for accessing production land of farmers and for accessing conservation lands of various tenures. The Acland Report suggests that a proposed access agency could be involved in developing a code of conduct 'in conjunction with tangata whenua, landowners, users and central and local government,'[39] and the Cabinet paper of December 2004 continues the theme.[40] A Code of Conduct could serve to educate the public about rural and conservation issues. It would have to include details of how to behave on private land; acknowledging private property rights, staying away from stock, crops, homes and curtilage, looking after fences and gates, and emphasise the allowance for walking only - without pets, vehicles and firearms. It could also appropriately include generic information about environmental respect and appreciation. Furthermore, it would be useful to have site specific information available, noting local environmental issues; problems and protections, the uniqueness of habitat and heritage, and enhancing a sense of place.

The Department of Conservation records a 10 point Environmental Care Code Checklist in their publicity about walkways:[41]

- Protect plants and animals
- Remove rubbish
- Bury toilet waste
- Keep streams and lakes clean
- Take care with fire
- Camp carefully
- Keep to the track
- Consider others
- Respect our cultural heritage
- Enjoy your visit

Federated Farmers have also released a draft Code of Conduct[42] to assist with the provision of public access over private land and to build on the goodwill that exists between recreational users and landholders. There is no shortage of ideas and examples of appropriate codes of conduct.

CONCLUSION

New Zealand public lands of various designations extend for about 9.8 million hectares[43] and make up about 36 % of the country. Most of this public land is relatively inaccessible mountain and high country, and is undoubtedly a wonderful conservation asset. It provides for many of the public needs for access to land. However, we should now be focusing on more readily accessible rural tracks in close proximity to but just beyond our centres of population. We do need more access to our open countryside, but it does not always need to be connected to our riparian zones, and does not need to be our ecologically fragile high country.

Local rural walking tracks may be expensive to define and construct, but they provide for the needs of an urban population requiring the escape to the land. If the government is serious about providing more access for New Zealanders, it is the day walks that provide most appropriately for the needs of society and where most emphasis should now be put. If the public needs additional rights, they will inevitably need to be paid for. The government is illustrating its willingness to pay, in actions such as buying on the open market many high country stations to add to the conservation estate. Additional rights to riparian lands may need to be bought by the Crown for the public benefit. Walking access track additions will need to be negotiated for, and compensation given to the property right holders for the granting of access rights.

Local authorities should identify the demand for access and assess their rural lands for the supply of more access to land. This could be made part of a council's responsibilities to their residents. Negotiated land acquisitions for a specific and identified purpose are much more palatable for a landholder than arbitrary takings just because a property adjoins a water body.

New access lands should be established by a process of identification, planning, consultation and negotiation. Those lands should have public access as their sole or at least primary purpose, they should be well maintained by a public access agency, and they should be well signposted and promoted. Some tracks may be immediately alongside rivers, lakes or the sea, and one would expect many to be conveniently located near waterways because of our great attachment to the water, but they are just as likely to be located inland. They should be located to provide for all aspects of public enjoyment. These may include a variety of degrees of comfort and convenience, various landscapes and ecosystems, and different levels of remoteness and wilderness. But they should be developed with three principles in mind: private property rights should be respected, public rights should be clear and undisputed, and our productive and ecological environments should be protected and enhanced.

An access agency could lead us into such a future of well recognised and readily available access rights, but as has been illustrated in recent debate, the path to such certainty must be carefully negotiated with all stakeholders.

Note: Extracts from this paper were published in the *Otago Daily Times*, Wednesday, 3 August 2005. page 15. 'Time to put public access issue on right track.' This paper formed the basis of a presentation at the NZIS Conference: 'Back to the Future', Dunedin. 13 October 2005. 'Back to the Land: Negotiating Access'

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Legislation:

- Land Act 1948
- Walkways Act 1990
- Conservation Law Reform Act 1990
- Resource Management Act 1991
- Crown Pastoral Land Act 1998
- Foreshore and Seabed Act 2004
- Bill of Rights (Private Property) Bill 2005
- Countryside and Rights of Way Act 2000 (UK)

Case law:

- Attorney-General v Ngati Apa [2003] 3 NZLR 643.

ENDNOTES

1 Or as Carew & McQueen 2000 state at 81: "there will remain a disparity between urban reality and public self-image" – that image being "one of mountains, bush, lake, river and sea."

2 Land Access Ministerial Reference Group. The Acland Report 2003.

3 Attorney-General v Ngati Apa [2003] 3 NZLR 643.

4 Strack, M. (2003, 2004a, 2004b).

5 See Hayes B 2003.

6 Lord J. Russell to Governor Hobson. 9 Dec 1840. Instructions.

7 A system that was appropriate and successfully implemented in the flat prairie provinces of Canada.

8 See paragraph 43. Instructions. Lord J. Russell to Governor Hobson.

9 Baldwin 1997 at 65, estimates that 50% of rivers (defined as 3m wide) and coastlines may have some sort of marginal strip.

10 Land*online* (www.landonline.govt.nz) is the official online database for all land/property information, although there are other proprietary products available that record and display similar land information – boundaries, tenure, property rights holder, etc.

11 See Baldwin, A.J. (1997).

12 These words refer to s232 (5)(c) which are the matters the territorial authority needs to consider when deciding if the provisions for a taking may be modified.

13 Collier, K. J., A. B. Cooper, et al. (1995). At p.4 other functions of a well vegetated riparian zone are listed: Buffers banks from erosion, buffers channels from localised changes in morphology, buffers input of nutrients, soil, microbes and pesticides in overland flow, denitrifies groundwater, buffers energy inputs, provides in-stream food supplies and habitat, buffers floodflows, maintains microclimate, provides habitat for terrestrial species, maintains dispersal corridors.

14 For example see http://www.fedfarm.org.nz/media%20releases/PR249-03.html "The vast majority of farmers allow access if asked. For courteous, responsible users, there is no lack of access to private property."

15 CPLA 1998 Section 24 (a)(i)

16 CPLA 1998 Section 24 (a)(ii)

17 CPLA 1998 Section 24 (b)

18 CPLA 1998 Section 24 (c) (i)

19 Waite L. 2005.

20 See for example Otago Daily Times 07 October 2005. p11 report on tenure review of Otamatapaio Station at Lake Benmore "Department of Conservation signs have to be put in place before the public can access the areas.

21 See for example, Wallace & Rae, Otago Daily Times, Wednesday, January 28. 2004. page 2. "High country sale has raised expectations: MP"

22 Crown Pastoral Land Act 1998. Section 2 Interpretation.

23 Cuddihy, M. Canterbury Conservator for DoC.

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25 Cuddihy, M. 2005.

26 A specific recommendation of the Land Access Ministerial Reference Group. 2003.

27 Walkways Act 1990 Section 3. General Purpose of Act. Subsection (1)

28 Walkways Act 1990 3.(2)

29 Section 23 Walkways Act. For example; no fires, no firearms, no dogs, no vehicles, no damage, etc.

30 Office of Minister for Rural Affairs 2004 para 16.

31 New Zealand Bill of Rights (Private Property Rights) Amendment Bill. Member's Bill introduced 8 April 2005. This would represent an almost constitutional protection of property rights equivalent to many other constitutions – for example the 5th Amendment of the US Constitution.

32 MAF 2005.

33 As quoted in McDonald 2005 at 15.

34 The Acland report was commissioned by Hon Jim Sutton (Minister of Agriculture in 2003) and coordinated by the Ministry of Agriculture and Forestry – MAF.

35 See Peter Scott Planning Services 1991.

36 Similar legislation has also been introduced in Wales and Scotland

37 Countryside Agency 2005

38 A website, cartoon characters, leaflets and free phone contacts promote the code.

39 Land Access Ministerial Reference Group 2003 at 74 and 79

40 Office of the Minister for Rural Affairs. 20 December 2004. at paras. 38-43.

41 DoC 2005b

42 Federated Farmers 2004.

43 DoC 2005a.

K. SMITH

HSA Systems Ltd
ksmith@hsa.co.nz

G. COX

Discovery Marine Ltd
discoverymarine@xtra.co.nz

Zones of confidence for New Zealand

ABSTRACT

In July 2004 HSA Systems Ltd (HSA) commenced an 18 month project for Land Information New Zealand (LINZ) to assess and assign Zones of Confidence (ZOCs) to all hydrographic surveys incorporated within 138 hydrographic charts of New Zealand. The project required each hydrographic survey to be assessed in relation to the data quality aspects of the International Hydrographic Organisation (IHO) S-57 Standard. During the survey assessment process the project team was cognisant of the Australian Hydrographic Service, RAN recommendations and experience with ZOC assessment. The application of an extensive local knowledge of hydrographic surveying practices undertaken in New Zealand was crucial to the project.

This paper will describe the process by which HSA assessed in excess of 1,792 hydrographic survey fair sheets and allocated 1,465 ZOCs to survey areas. ZOC metadata and polygon coordinates were captured using the IHO S-57 version 3.1 format prior to export in eXtensible Markup Language (XML) format.

KEVIN SMITH is the Manager (NZ Business Group) for HSA Systems Ltd in Wellington, New Zealand. Kevin joined HSA in 1997 after 15 years of hydrographic and GIS experience with the Royal New Zealand Navy Hydrographic Service.

HSA's New Zealand business group provides a wide range of services to the New Zealand Government and maritime community.

GREG COX is the Managing Director and IHO CAT A Surveyor at Discovery Marine Ltd (DML). Greg established DML in 1997 after 10 years as a hydrographic surveyor with the Royal New Zealand Navy Hydrographic Service.

DML provides a specialised range of hydrographic and marine services for coastal projects. The company's skills in the hydrographic survey industry are based upon key personnel with many years of experience in planning, conducting and producing accurate hydrographic surveys for national and international charting requirements.

INTRODUCTION

To date, New Zealand has provided quality indicators on all of its hydrographic charts by way of Source Data Diagrams and Diagrams of Sounding Line Density. To address the current hydrographic data quality requirements, LINZ required the capture of ZOC information for their hydrographic surveys.

The purpose of this paper is to provide an overview of how the ZOC information was acquired including a discussion on the data sources, assessment and encoding approach.

ZONES OF CONFIDENCE (ZOCS)

A concise history of the development of ZOCs and their adoption by the International Hydrographic Organisation (IHO) is described by Johnson (2004). Aspects of Johnson's paper are briefly restated here in order to provide an overview of ZOCs. During the 1990s the concept of ZOCs was developed by'the Australian Hydrographic Office (AHO).

The IHO Data Quality Working Group (DQWG) developed ZOCs as a technically feasible solution for the assessment and display of hydrographic data quality to support safe and efficient navigation.

The method of encoding data quality information as a ZOC is contained within the IHO Special Publication No. S-57, Transfer Standard for Digital Hydrographic Data, which includes the Feature Object 'M_QUAL' and the attribute 'CATZOC"– Category of Zone of Confidence in Data (ZOC).

Areas covered by hydrographic surveys are classified by identifying various levels of confidence with respect to depth accuracy, position accuracy, thoroughness of seafloor search, and the characteristics of the survey.

Six ZOC have been developed - A1, A2, B, C, D and U and these are described in Figure 1. ZOC A1, A2 and B are typically for

ZOC	Position Accuracy (m)	Depth Accuracy (m)	Seafloor Coverage
A1	± 5.0	= 0.5 + 1% depth	full area search undertaken; all significant seafloor features detected have had depths measured.
	Typical Survey Characteristics (see Note): controlled, systematic, high accuracy survey on WGS 84; using DGPS or a minimum 3 lines of position with multibeam, channel or mechanical sweep system.		
A2	± 20	= 1.0 + 2% depth	full area search undertaken; all significant seafloor features detected have had depths measured.
	controlled, systematic survey; using modern survey echosounder with sonar or mechanical sweep.		
B	± 50	= 1.0 + 2% depth	full area search not achieved; uncharted features, hazardous to navigation, may exist.
	controlled, systematic survey.		
C	± 500	= 2.0 + 5% depth	full area search not achieved; depth anomalies may be expected.
	low accuracy survey or data collected on an opportunity basis such as soundings on passage.		
D	worse than ZOC C	worse than ZOC C	full area search not achieved; large depth anomalies may be expected.
	poor quality or data that cannot be assessed due to lack of information.		
U	quality of bathymetric data yet to be assessed.		

Figure 1. Zone of Confidence (ZOC) Assessment Criteria

modern surveys with A1 and A2 requiring a full area sea floor search, C and D reflect low accuracy, low density and/or poor quality data whilst U represents data which is unassessed at the time of publication. ZOC criteria are summarised in Figure 2.

NEW ZEALAND'S REQUIREMENT

LINZ is New Zealand's national charting authority. LINZ had a requirement to capture, document and present the ZOC information for surveys used in the compilation of New Zealand's hydrographic charts. ZOC assessments were to be undertaken on a survey basis as opposed to a chart basis i.e. ZOC diagrams for individual charts was not a specific product of this project.

LINZ (2004) contracted HSA to undertake this project with the project outcomes being:

- Provide a detailed understanding of the quality of all hydrographic surveys used in the compilation of New Zealand's larger scale nautical charts;
- Improve the survey prioritisation process; and
- Allow for the future depiction of ZOC diagrams on LINZ's paper charts and electronic navigational charts (ENCs).

ZOC	Summary Criteria
A1	all significant seafloor features detected; very high accuracy survey.
A2	all significant seafloor features detected; high accuracy survey.
B	uncharted features dangerous to surface navigation are not expected but may exist; medium accuracy survey.
C	depth anomalies may be expected; low accuracy survey.
D	large depth anomalies may be expected; low accuracy survey.
U	quality of bathymetry yet to be assessed.

Figure 2. Zone of Confidence (ZOC) Summary Criteria

PROCESS OVERVIEW

The first step in the project was to undertake a desktop assessment of the number of potential hydrographic surveys used in the compilation of each hydrographic chart. LINZ identified 138 large to medium scale charts requiring assessment, each with its own chart index. The chart index is the key document providing an indication as to which surveys had been used to compile each chart. The chart index is the document from which the Source Data Diagram is compiled and portrayed on the printed paper and raster chart. The desktop assessment indicated approximately 484 surveys consisting of 1,946 fair sheets had been used in the production of these charts.

With the approximate volume of fair sheets identified the process for assessing the survey sheets for ZOC classification was determined and refined – refer to Figure 3.

The process required the largest scale surveys affecting the largest scale charts to be assessed first. In this way smaller scale surveys/charts and overlapping charts would only need the surveys assessed which fell outside of the larger scale surveys. Each chart index was extracted from the LINZ Hydrographic Data Repository (HDR) along with all of the surveys used in the compilation of that chart. Any ancillary information accompanying each survey i.e. reports of survey, tidal data packs, geodetic data packs etc were also extracted as they are required for full ZOC assessment. Each survey was then evaluated and awarded a ZOC classification. This information was recorded in the project documentation and encoded in an S-57 database. The ZOC polygons were then digitized and tagged with the encoded

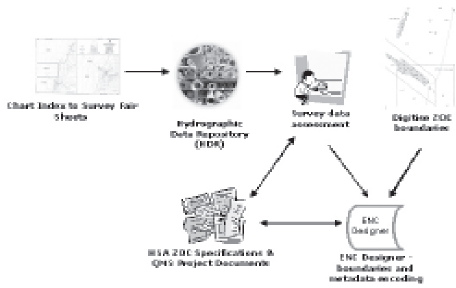

Figure 3. ZOC Assessment Overview

metadata.

TOOLS

A key element of the capture, storage, access and dissemination of the ZOC attribute information are the tools with which this information is processed and retained. In New Zealand's case the requirement was for the mass assessment, capture and population of a ZOC attribute database or databases. The databases needed to be populated with ZOC metadata in conjunction with the ZOC/survey polygons. A mechanism by which all of this data could be quickly and readily validated with a high degree of confidence was also required. Two tools were evaluated for the purpose.

ZOCMAN

The Australian Hydrographic Office (AHO) developed the ZOCMAN application in 1999. ZOCMAN was originally developed for the MS Windows 95/NT platform and was compatible with the Borland Database Engine (BDE) 4. ZOCMAN records ZOC metadata, calculates the ZOC rating based on a defined algorithm and enables the operator to encode ZOC/survey coordinates for a single polygon. ZOCMAN allows the operator to manually enter ZOC polygon coordinates. An additional GIS application, such as MapInfo, is required for polygon capture via digitiser. No degree of topological structure is maintained while the spatial aspect of each ZOC polygon must be viewed independently to the metadata. The ZOC metadata and spatial data is stored in a Borland database format. There is only a limited ability to provide information to other applications without additional processing.

ENC Designer/AutoZOC Module

ENC Designer is a software tool used in the production of S-57 Electronic Navigation Charts (ENCs). The product was developed by **SevenCs AG & Co. KG**. ENC Designer operates on the MS Windows XP Pro platform. The application uses topologically structured data at the chain-node topology level which is consistent with IHO S-57. All exported spatial topology will correctly handle islands and holes in ZOC regions. A key aspect of ENC Designer is the ability to export data as an S-57 v. 3.1 ENC data set. The ZOC ENC cells/databases are therefore easily maintained and disseminated. The ENC cells can be viewed using any of the available ENC viewer applications. With ENC Designer, the user has the benefit of a single software interface to encode both ZOC attribute data and spatial data. Customised object catalogues can be created to cater for additional attributes. There is also an ability to load TIFF images as a back drop for polygon capture, identifying changes and assisting with quality assurance.

HSA developed the AutoZOC plug-in module for ENC Designer. The module incorporated and improved the AHO's ZOCMAN assessment logic flow chart – refer to figure 5. AutoZOC is invoked from within ENC Designer. The determination/confirmation of a ZOC rating occurs within the AutoZOC module which reads the parameters (made available in the customised object catalogue) and automatically populates the S-57 CATZOC attribute. AutoZOC reads and writes to the S-57 file which ENC Designer generates. The ZOC metadata can then be exported in XML format. XML is supported by most modern Geographic Information Systems (GIS) hence the ability to easily migrate the ZOC data to a platform of choice. In LINZ's case, HSA developed the AutoZOC-DB schema for importing XML data into a MS Access database. AutoZOC-DB contains an AutoZOC calculator. This is purely a validation tool as you cannot actually populate or change a CATZOC value at this stage.

Given LINZ's requirements for the level of metatdata to be recorded, the storage and dissemination of ZOC data, ENC Designer, including the AutoZOC module, was determined to be the appropriate solution for this project.

METHODOLOGY

Skill sets

A key requirement for the project was the need to have qualified and experienced hydrographic survey personnel. A Cat A surveyor was appointed to lead the team. This surveyor's role was to finalise and approve the ZOC classifications assigned to surveys and to ensure that an identical assessment logic was applied to all surveys. A Cat B equivalent hydrographic surveyor was responsible for all of the initial research and assessment of surveys, metadata capture and record keeping. Both surveyors had an extensive knowledge of hydrographic surveying practices within New Zealand. An experienced hydrographic cartographer familiar with New Zealand cartographic practices provided input in terms of how surveys were implemented on New Zealand charts.

Given the familiarity of the surveying staff with a wide variety of software applications for hydrographic data management and processing it was a straight forward task to train staff in the use of the ENC Designer software.

Cell/database management

New Zealand's area of charting responsibility is large as it encompasses islands from just south of the equator to Antarctica. It was necessary to create three separate cells or databases based upon geographic regions; Pacific Islands, New Zealand, sub-Antarctic Islands and Antarctica.

It should be noted that at any stage it is possible to integrate any number of cells/databases back into a single master cell/database using ENC Designer. In this way, ZOC data could be managed and quality assured in discrete units. Each cell/database can be loaded, exported and backed up individually.

Digital Index Chart Capture

The next step in the process was to scan and geo-reference chart indexes in order to provide a raster backdrop for loading into each cell/database. This provided a facility for survey boundary capture and quality assurance. The chart indexes were scanned and output as 300 dpi, black and white TIFF images. Using ENC Designer the TIFF images were individually geo-referenced. The TIFF images were provided to LINZ for internal use and as a digital back up of the paper chart indexes.

Surveys Identified for Assessment from Chart Index

A detailed database of surveys and associated documents was then built from the chart indexes prior to extraction from the LINZ Hydrographic Data Repository (HDR). A team of people was assigned to extract the necessary records from the HDR for assessment. The extraction and return of all records was controlled using HSA's Quality Management System (QMS) as nearly all of the records are originals with some dating back to the 1800s.

ZOC assessment

The ZOC assessment process was carried out on a survey-by-survey basis commencing with the largest scale surveys. The ZOC assessment teams task was to:

- Examine each survey sheet.
- Examine associated reports for information on survey method used and survey accuracies.
- Determine the surveying method used, ZOC category for position and depth accuracy.
- Determine the ZOC category for seafloor coverage for each survey.
- Where necessary, subdivide the survey into areas of different seafloor coverage and assign appropriate ZOC ratings.
- Seek advice or guidance from LINZ as required.
- Record all ZOC assessments using project documentation controlled by HSA's ISO 9001:2000 Quality Management System.

The AutoZOC calculator tool was developed to assist with assigning a ZOC rating. Based upon the IHO ZOC rating criteria, an assessment logic was developed and incorporated into the AutoZOC tool – Refer to Figure 4.

As the assessment process progressed a picture was built up of the types of surveys undertaken in New Zealand and their approximate ZOC rating. This is summarised in Figures 5 and 6.

A key point to note from the statistics in Figure 7 below is the figures in the 'Reality'

Figure 5. New Zealand Survey techniques & approximate ZOC rating

Years	Sounding Technology	Depth Accuracy +/-	Positioning Technology	Positioning Accuracy	Broad ZOC Group
Pre 1900	Leadline	0.2 - 5.0??	Sextant	10 - 1000m	D
1900 - 1967	SBES	0.1 - 2.0	Sextant	10 - 200m	D,C
1900 - 1991	SBES	0.1 - 1.0	Terrestrial Fixing (large scale)	3 - 5m	B
1950's - 1987	SBES	0.1 - 1.0	Hifix6	5 - 30m	B/C
1978 - 1985	SBES	0.1 - 1.0	Trisponder RO3	2 - 8m	B
1985 - 1993	SBES	0.1 - 1.0	Trisponder DDMU	2 - 8m	B
1980 - 1990	SBES	0.1 - 1.0	SatNav	200m	C/D
1983 - 1993	SBES	0.1 - 1.0	GPS S/A	50 - 130m	C
1998 - 2004	SBES	0.1 - 1.0	GPS (no S/A)	6 - 12m	B
1992 - 2004	SBES	0.1 - 1.0	DGPS	1 - 3m	B
1998 - 2004	MBES	0.1 - 1.0	DGPS	1 - 3m	A1 or A2
1995 - 2000	SBES	0.1 - 2.0	GPS (Centurion Coded)	6 - 12m	B
Various	SBES	0.1 - 5	U	Unknown	D
Various	SBES	0.1 - 2.0	Radar/Bearing	0.02 - 0.2nm	D

Comments: *Column 1 – Estimates,. needs to be refined from information within ROS's.*

Column 2 & 4 – There are a number of other sounding and positioning combinations that may arise through research of historic data. Each will need to be assigned a ZOC rating based on own merits. MBES is not operated without DGPS as a minimum positioning control.

Depth Accuracy. This can be extremely variable depending on all factors associated with vertical accuracy – such as tides etc.

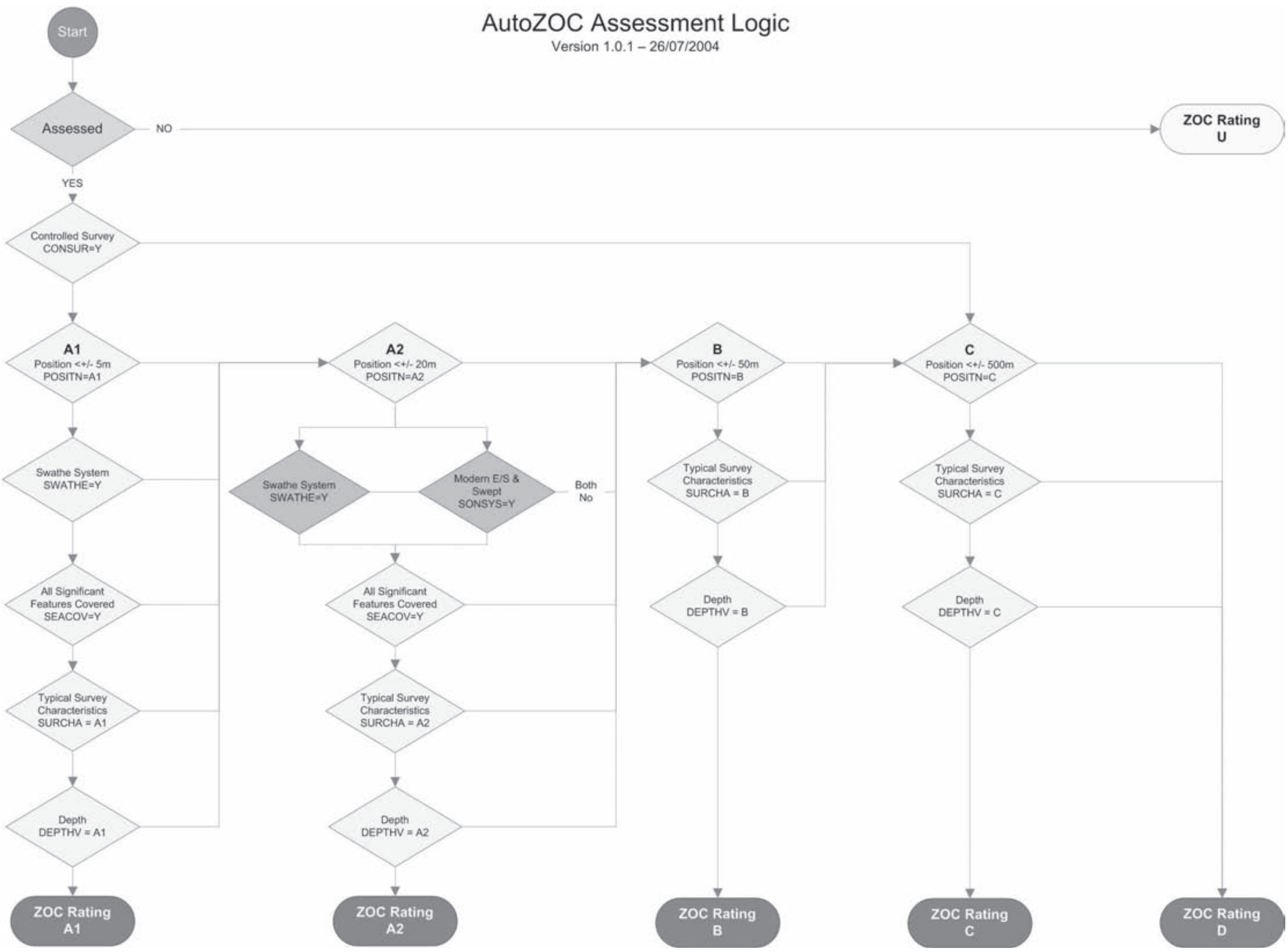

Figure 4. Improved Australian Hydrographic Service ZOCMAN assessment logic flow chart for use in the AutoZOC calculator

column exceed those from the 'Desktop Study' column. This was due to inconsistent chart indexes. It should be noted the chart indexes were never meant to be used as comprehensive source document indicators for a ZOC analysis.

ZOC ENCODING PROCESS

Figure 6. New Zealand Surveys & approximate ZOC rating

Survey Type	Broad ZOC Group	Scale/Accuracy
Gebco	D	500m
OSS	D	500m
Misc	C/D	Individual Basis
Pre 1970's	C/D?	Individual Basis
Offshore/Navy	B/C	As per specs
Inshore	A/B/C	As per specs
Side scan sonar	A2?	As per specs
Lachlan 1950's	C	75000/100 200000/200
Lachlan 1972/3	B	As per specs (fitted with metric sounder)
Monowai 1980's	B/C	As per specs
GPS 1990's	B+	As per specs

The ZOC encoding process involved the following stages:

1. Encoding Metadata
2. Polygon capture
3. ZOC cell XML export

The encoding of metadata required a set of documentation to be created which duplicated the fields to be populated within ENC Designer. This would serve two key purposes:

1. Provide a hard copy record signed by the authorising surveyor. In New Zealand's case this was a senior Cat A surveyor.
2. Provide a 'paper' back up to the digital equivalent in case of the database becoming corrupted or lost in any way.

The encoding forms were populated from the surveyor's ZOC assessment records.

Figure 7. Total Surveys Assessed

Desktop Study	Surveys Indexed	484	Sheets Indexed	1,946			Charts Required	138
Reality	Surveys Actually Assessed	731	Actual Survey Fair Sheets	1,792	Other (Gebco, OSS, Sketch, Misc)	192	Charts Assessed & Encoded	138
		151.03%		**92.09%**				**100%**

Encoding used the object editor mode within ENC Designer. The AutoZOC calculator was used to confirm the ZOC rating. ENC Designer automatically generated unique object identifiers for each record. The operator populated compulsory fields and other fields where information was known. The INFORM – Notes field was used to document additional information.

Each ZOC metadata record had to be associated with a polygon boundary. The polygon boundary was captured and tagged with the ZOC metadata. The polygon digitising and editing process within ENC Designer was undertaken in geometry mode. Polygon boundaries were captured with line/node editing undertaken using the features such as snap/split/latch while at the same time maintaining polygon topology.

WORK FLOW

Given the size of the ZOC assessment and projected encoding, a small port located on the South Island of New Zealand was selected as a trial area in order to refine the ZOC processing model. This area incorporated a range of survey types from large scale harbour surveys, sidescan surveys, medium scale approach surveys, smaller scale coastal passage surveys and oceanic GEBCO passage sounding. Once completed and accepted, the ZOC assessment and encoding process began in earnest with the order of priority being the Pacific Islands, Antarctic and finally New Zealand. Refer Figures 8 and 9.

The table above provides information on the numbers of ZOCs in each cell/database.

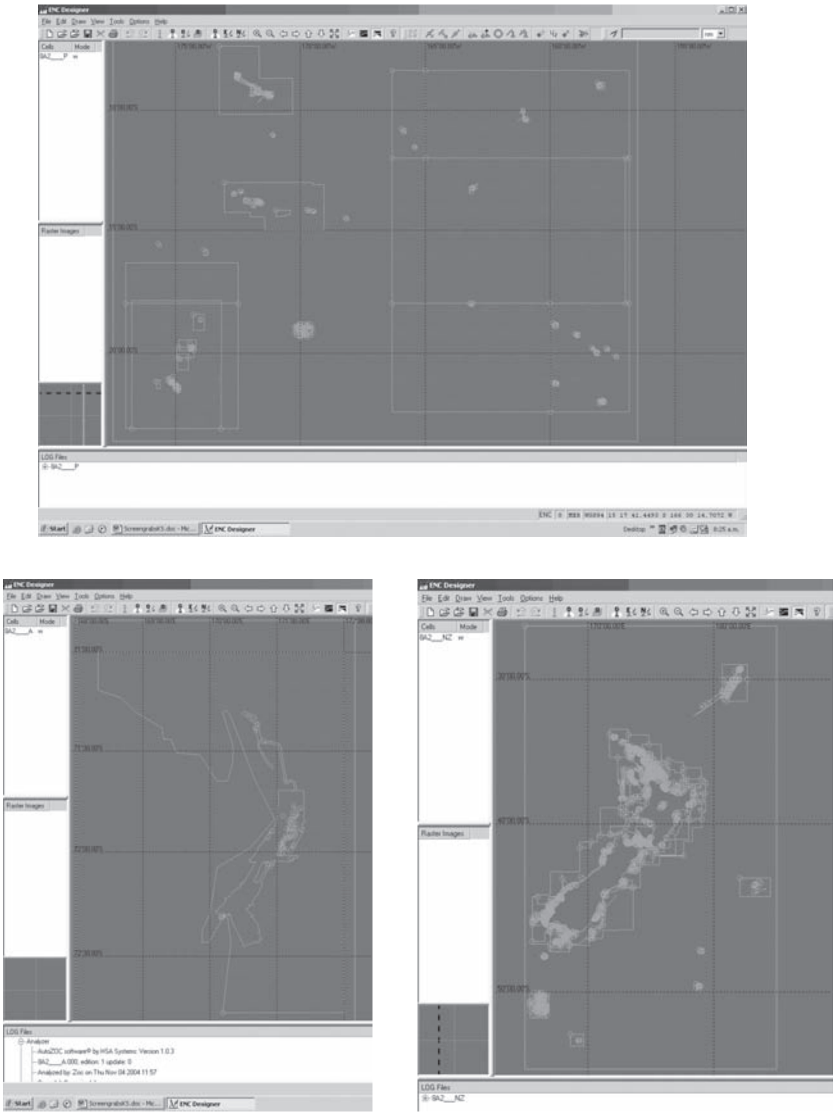

Figure 8. Pacific Islands, Antarctic and New Zealand cells/databases

Figure 9. Wellington Harbour, detailed view, New Zealand cell/database

Cell/Database	A1	A2	B	C	D	U	Total Number of ZOCs
Pacific Islands	1	3	27	40	98	19	188
Antarctic	0	4	2	0	0	1	7
New Zealand	2	66	429	302	157	314	1,270
							1,465

QUALITY ASSURANCE

The project was undertaken in accordance to HSA's Quality Management System (QMS) which is certified to ISO 9001:2000. LINZ and HSA implemented detailed contract specifications, project plans and quality plans. Each survey was assessed by an experienced hydrographic surveyor then quality controlled and approved by the Cat A surveyor. As well as manual checks of all records ENC Designer provided integrity reports for data captured within ENC Designer. This resulted in a quick and efficient method for correcting data entry errors.

PROJECT DELIVERABLES

At the completion of the project the following deliverables were supplied to LINZ:

1. 1 x TIFF file of each index chart (138)
2. 1 x ZOC assessment folder for each chart
3. 1 x XML file for each cell/database
4. Populated AutoZOC database (MS Access)
5. 1 x S-57 v 3.1 ENC cell for each cell/database
6. Summary Report

A key aspect of the data supplied to LINZ was the portability of the digital data in XML format. This permits LINZ to readily migrate the ZOC data to its platform/s of choice for future data capture, maintenance and distribution purposes. This is demonstrated in the following views whereby the ZOC boundary data and metadata has been migrated into the freely available Google Earth web browser.

CONCLUSION

The project was commenced in June 2004 and was principally completed by late June 2005, approximately five months ahead of schedule. The gain in timing can be attributed to:

- The use of experienced hydrographic surveyors with extensive knowledge of New Zealand surveying practices.
- The use of the ENCDesigner software which enabled both the spatial and attribute data to be captured and managed within the one application.
- A well documented process for ZOC assessment.
- Clear and concise operational and contract documentation.

Given the ZOC assessment process required a review of all hydrographic surveys used in New Zealand's nautical charts, it was

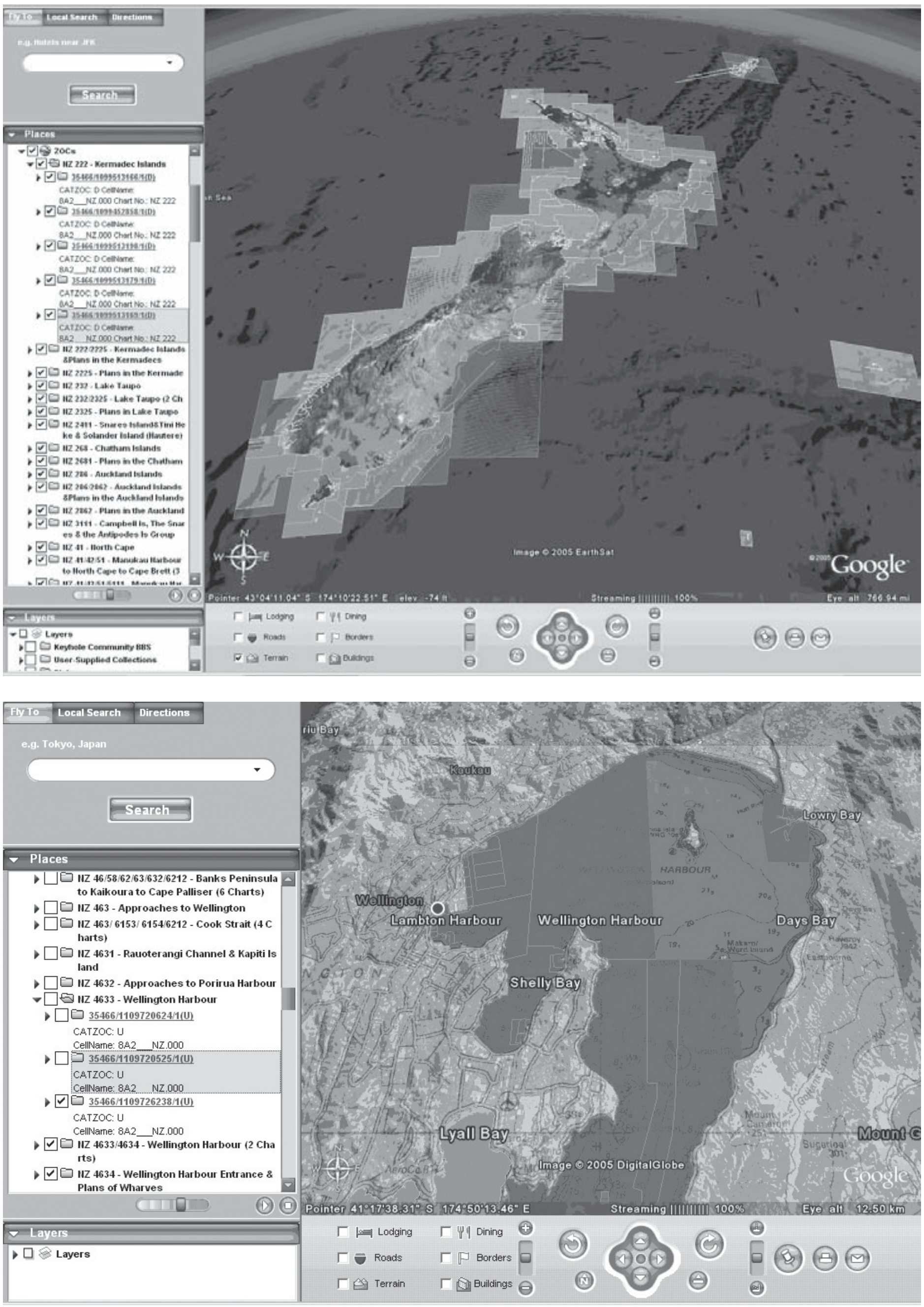

Figure 10. New Zealand cell/database and Wellington Harbour, detailed view with chart backdrop, within Google Earth

clearly evident that there was a diverse range of quality and age in the surveys reviewed. Documentation associated with the surveys, including reports of survey, varied greatly. With modern technologies for hydrographic surveying now readily available, including detailed survey specifications produced by national and international bodies, the quality for metadata accompanying surveys should be high. Most local and national agencies responsible for undertaking hydrographic surveys are now required to manage risk. One method for understanding that risk is the assignment of ZOC ratings to hydrographic surveys. This can only be accurately undertaken if a survey is accompanied by supporting information on how the survey was undertaken and to what specifications the data has been gathered.

The information gathered during this project provides LINZ with a detailed view of surveys used in chart production, e.g. their accuracy, age and extent. With this data LINZ can now better identify and prioritise areas which require surveying and programme the release of ZOC information in its products.

ACKNOWLEDGEMENTS

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MICHAEL BARRY

University of Calgary
email: barry@geomatics.ucalgary.ca

Boundary systems in informal settlement upgrades: Imizamo Yethu settlement in Cape Town

ABSTRACT

At the time of South Africa's transition to democracy in 1994, a number of options for land tenure types and boundary systems were proposed for upgrading informal settlements. Proposed tenure types included individual parcels held under individual ownership, family ownership of individual parcels, and block ownership under communal property associations. Boundary types included fixed boundaries, general boundaries, fixed boundaries for block corners and general boundaries internal to a block, and a mid-point cadastre where dwellings were referenced to a single monument.

This paper describes a study of the boundary types and the nature of boundary disputes in the Imizamo Yethu settlement in Cape Town over a period of 13 years. The study included aerial surveys of as built structures overlaid on the legal cadastral maps, interviews with residents, community leaders, officials and surveyors, and monitoring of the case study up to a recent resurvey of the settlement. It was found that fixed boundaries have been suitable in this settlement, although some improvements could be made to the manner in which they were handed over and managed.

MIKE BARRY is an Associate Professor in the Geomatics Engineering Department at the University of Calgary, where he his Associate Head of the Undergraduate programme. He has BSc(Survey) and MBA degrees from the University of Cape Town and a PhD from the University of Natal. His research interests are in developing software tools to support land tenure, analysing and managing change in applying cadastral systems and spatial data analysis. Prior to moving to Canada in 2002, he spent 11 years in private practice and local government and 12 years in the Department of Geomatics at the University of Cape Town. He was recently appointed a director of the FIG Foundation.

INTRODUCTION

South Africa has long been at the forefront of developing an integrated cadastral survey system, where coordinates tied to the national geodetic control can be established for the majority of the parcel corners in the country. In many of the urban areas the majority of the corner monuments have been coordinated to a high precision. For example, when the City of Cape Town generated the cadastral layer for its municipal GIS in the 1980s to establish coordinates of parcel corners which had not be coordinated in surveys linked to geodetic control, the tolerance for closure of data traverses between monuments which had been surveyed and coordinated was of the order of 10 cm. Exceptions were in areas which had been developed more than 150 years ago and in which few cadastral surveys had taken place subsequently. In these areas the most probable positions of boundary corners were reconstructed and coordinated using the best evidence available.

This integrated, coordinated cadastral survey system has been developed incrementally since the late 19th century. The approach has been to legislate that cadastral surveys be coordinated on the national mapping system and tied to geodetic control as it became logistically feasible to do so. By 1939, all rural cadastral surveys had to be connected to the trigonometrical control network (Fisher et al 1982). Requirements to connect urban surveys to geodetic control were not as stringent until the 1970s when EDM technology developed and cadastral surveys of parcels within a specified distance from urban geodetic survey control monuments had to be tied to them. The specified distance was gradually increased as the range of infrared EDMs increased, and since the early 1990s all cadastral surveys have had to be coordinated on the geodetic control system.

Consequently, when political negotiations commenced in 1990, the country had an integrated cadastral information system that was arguably a world leader in the technical sense. However, only people classified as white, coloured or Indian under the apartheid system could enjoy the benefits of it in owning land. With some exceptions, under the apartheid system, black Africans could only hold occupation rights under a permission to occupy (PTO) certificate in the homelands and other land scheduled for their occupation. Moreover, although blacks constituted 80% of the population, they had access to occupation rights in only 13% of South Africa's surface area. It was only after the first reforms in the 1980s that they were allowed to hold land under 99-year leasehold in urban areas in terms of the Black Communities Development Act 4 of 1984. Most of the current land reform, land restitution and housing programmes which were first considered at the time of these negotiations have had to address the skewed distribution of land as well as the disparities in legal land tenure forms.

One of the debates that took place in parallel with these political negotiations was the role of the land surveyor in post-apartheid South Africa. Questions which came under the spotlight were land tenure types, appropriate land registration systems, and boundary and cadastral survey system options. It is the latter, boundaries and surveying options, which are the focus of this paper. First, some of the proposals that were put forward at the time are described. This is followed by a description and analysis of the Imizamo Yethu case where, among other land tenure management issues, the effectiveness of cadastral boundaries and boundary monuments has been studied since 1992.

PROPOSALS FOR BOUNDARY TYPES

The South African Council for Professional and Technical Surveyors (PLATO) commissioned a study on options for the cadastre in the New South Africa " as it came to be known " by Dr Clarissa Fourie. The study identified some 30 factors that had to be taken account. These included the need to build around 200,000 houses per annum (in 2005 some 1.8 million had been built), facilitate the redistribution of 30% of the land to Blacks in five years (this has not happened), and provide the necessary land information to identify suitable land for the land reform programme and provide evidence for the land claims process (Fourie 1994).

In terms of boundaries and cadastral surveys, the following options were explored and a number of scenarios were mooted:

1. Use a form of communal or group title and not survey internal boundaries of rural small holdings or parcels inside a block in urban areas. This incorporates the notion of blocks and superblocks, which were used in the Solomon Islands in the 1960s (Fourie 1994). Other authors have also proposed this system as being appropriate for developing countries (e.g. Jeyanandan and Williamson 1990). The author advanced this concept of surveying and registering an outside figure further as a means to stimulate densification of urban areas in the long term. Individual parcels create sprawl, and in the case of the poor, the costs of travelling to places of economic opportunity is often higher than what people earn. Using a communal title or a form of shareblock, a community can settle initially and determine their own individual boundaries within an outside figure. Later perhaps they may choose to develop a multi-storey building on their block. Thus the block title can be seen as an opportunity for property development in the long term and a strategy for demand driven urban densification (Barry 1995).
2. General boundaries to replace the existing system of fixed boundaries or to co-exist with the fixed boundary system. The general boundary system could be augmented by photogrammetric surveys of the physical features giving effect to these boundaries to create coordinates of them as evidence, and for planning, engineering services design and administrative purposes (Fourie 1994). There are major initial cost advantages to general boundaries in situations where full engineering services are not envisaged in the immediate future. However, in the author's experience, starting with general boundaries and a weak form of individual tenure and then converting it to ownership with fixed boundaries later can, purely from a surveying perspective, be a very expensive exercise (eg Clifton Bungalows site in Cape Town). More pertinent to a post conflict society, Fourie (1994), drawing on interviews with a number of international authorities, posited the following: '*General boundaries do not work within and between hostile communities where boundary disputes between neighbours require clear objective evidence rather than a semi-flexible boundary. However, general boundaries work well in tolerant communities with good conflict resolution mechanisms.*'
3. Create a range of surveying and registration options. The risk of this option was the perceptions it might create. Blacks had had an inferior tenure system of occupation rights, whereas other South Africans had access to ownership. Such a distinction could not be perceived to continue by those who were supposed to benefit from land reform and land restitution.
4. Mid point systems – as a start a group could have a single monument placed in the ground and against which descriptions and/or measurements to a number of dwellings could be made when registering rights (Jackson 1996). Fourie (1994), drawing on preparatory work by Jackson (1996), notes that:

> '*This approach could be used specifically for informal settlements, or where some kind of weaker individual right within a group right is required. The approach would involve: a coordinate (a unique identifier which dovetails with our present system), over a stake in the ground (the physical cadastre) next to a house, and linked to a paper record of who held that right (contained in a community register updated regularly by the local leadership)*'. One advantage of this approach is that it provides a rapid means of providing some form of tenure security. However, in my opinion, it is not clear why it is necessary to use a stake in the ground to do this rather than use the shack itself as evidence of land rights. For example, most informal settlement upgrading systems in Cape Town worked on a rent card which noted the occupants' personal details, and the card was often referenced by a number painted on a shack. Utilities suppliers also worked on a system of numbers painted on the side of the shack. Thus the use of a mid-point monument appears to be superfluous as the shack and the number painted on it provide adequate evidence of occupation and a unique numeric identifier that can be used in manual filing systems and computerised information systems.

These options, along with options for tenure types and registration, were then explored in a number of working groups, in which the author participated, which were set up by the minister of land affairs after the first democratic elections in 1994. Several case studies were established by the government, and the author initiated five case studies in the Cape Town area. Imizamo Yethu is one of these cases.

IMIZAMO YETHU HISTORY

Imizamo Yethu, meaning 'through collective struggle' in Xhosa, was a site-and-service scheme situated on 18 hectares of land made available to accommodate squatters in Cape Town's suburb of Hout Bay. Up to the 1980s, the valley was predominantly rural with large tracts of marginal agricultural land. However, the area has developed rapidly as an upper middle class urban area (Nathan and Spindler 1997).

Squatting occurred sporadically in pockets dating back to the 1940s. By late 1990 more than 2000 people lived in five informal settlements (Gawith and Sowman 1992). Collective action by informal settlers to obtain legal property rights and the reaction to the informal settlements from existing property owners in Hout Bay forced the authorities to make formal property available for the squatters. Forestry land at Imizamo Yethu was made available in late 1990 and 429 sites were occupied as from March/April 1991 (Gawith and Sowman 1992, Oelofse 1994). These were registered squatters and the site was regarded as a transit area while the formal layout in the same vicinity was being planned. Planners at that time (May 1991) envisaged 700 parcels being created for 2400 people. However, by May 1992, there was pressure from the community for more land as new arrivals were laying claim to the buffer zones around the settlement (Nathan and Spindler 1997). By June 1997, an estimated 5000 people occupied the settlement and surrounding green belt areas and although much of the site has been developed, people continue to move in and there is further squatting on the periphery of the settlement.

The majority of the Imizamo Yethu community members are Xhosa speakers from the former homelands of the Transkei and Ciskei in the Eastern Cape, many of whom are recent arrivals in the City. There are also a number of Coloured people who hail from the historical Hout Bay squatter communities and some people from other parts of Africa such as Namibia, Angola and Zaire squatting on the periphery of Imizamo Yethu. Many of the latter group are illegal immigrants.

Surveying and demarcation of 429 parcels in phases I and III, with dimensions of the order of 10m x 15m, commenced in 1993. Two legal cadastral plans, phases I and III were surveyed, using fixed boundaries monumented with 12 mm iron reinforcing bars. In cases where people had already assembled their shacks which straddled a newly surveyed boundary, the household was supposed to move the shack to conform to the legal boundary that the land surveyor had set out.

For a variety of reasons, some of which are discussed below, a re-survey of phases I and III was done in 2003. Most of the survey has been completed, but there are some minor adjustments to the layout that are still ongoing.

DATA COLLECTION

Data collection included aerial surveys of the positions of shacks in the settlement, interviews with residents and other important role players, and ongoing monitoring of the case study.

Mapping of shacks using 1:10000 stereo imagery, which had been flown in December 1994, was overlaid on the legal cadastral maps. At that stage an insufficient number of fences had been constructed to draw meaningful analysis and so only the positions of shacks were mapped and analysed.

Twenty-five structured interviews and group discussion sessions were held in 1997 with a total of 42 home occupants. Eleven of these were individual interviews and the remaining 33 respondents were interviewed in small groups. To ensure that the sample was not biased by a large proportion of unemployed persons, the interviews were conducted outside of normal working hours at night and over weekends. To reduce spatial bias in the sample, at least one interview was held in each block in the formal layout of the settlement. The sample comprised 24 females and 18 males, and included nine coloured people. This was a reasonable reflection of the demographics of the settlement.

Monitoring

Ongoing interviews have been held with the surveyor who did the original survey of phases I and III in 1992, the surveyor who has been doing a resurvey of these areas since 2003, community leaders, officials, NGO employees, researchers, and other interested parties. Articles in the press have also been monitored as Imizamo Yethu often features in the commercial press due to conflicts between factions within the community, conflicts between the community and the municipality, and conflicts between the community, the municipality and surrounding middle class residents.

RESULTS

In phase I, the photogrammetric survey showed that 157 parcels had dwellings (shacks) on them in 1994. Of these, 21 parcels (13.3%) were interpreted to have shacks that encroached over neighbouring boundaries. Of these 21 parcels, three also had structures that encroached on the road reserve or on public land. In phase III, 105 parcels had shacks on them. Of these 29 parcels (28%) were interpreted to have shacks that encroached over the boundary.

Prima facie, these results suggest that a system of fixed boundaries, perhaps the system of individual parcels, or the manner in which the township layout was designed were inappropriate. Another possible explanation is that in instances where shacks existed on the ground at the time of the original cadastral survey, shack dwellers who were supposed to move their shacks so that they fell within the parcel boundaries did not do this. Thus further investigation was necessary.

The results of the interviews and group discussions involving Imizamo Yethu residents indicated that fixed, non-ambulatory, boundaries demarcated by monuments at the apices of the polygons defining the parcels are appropriate. In 23 out of 25 interviews / group discussions the response was that 'pins' (12 mm iron pegs) demarcate the boundaries. Moreover, participants showed positive attitudes to such a system. In the remaining two interviews, participants were ignorant of boundary concepts.

Using models, groups were then given a scenario where a neighbour inadvertently built a structure that encroached over their boundary and they were asked how they would react. With one exception, all the participants suggested that that they would evict the encroacher. However, a number of participants added the proviso 'unless there is an agreement', which will be elaborated on below. When pressed further what they would do even if the encroachment was only 1 cm over the boundary, in 17 of the sessions, the participants indicated that they would still evict the encroacher. Two groups explained that 'if you allow one centimetre today, tomorrow it will be more'.

Thus, the interviews and group discussions indicated that the system of boundaries used was appropriate. However, the question remains why there were a significant number of encroachments shown up by the aerial surveys. Failure to move shacks into the correct positions when the layout was surveyed may explain this. However, the encroachment patterns observed in Imizamo Yethu are in harmony with data collected from other similar case studies in Cape Town at the time, where large numbers of encroachments were also recorded (Barry 1999).

Land grabbing, at times by powerful individuals and factions in the community, does explain some of the encroachments. One community leader had assisted officials in allocating land and moving residents onto their surveyed sites in 1992. She could recall five cases where the first arrivals on their parcels had pulled out the monuments, the '12mm iron pins'. These monuments were either moved to enlarge the parcel or disposed of and the person(s) then built a structure that was larger than the parcel itself. Other informants suggested that boundary monuments were stolen (and possibly sold to scrap metal merchants) or used as tools and thus when people built a shack they did not know where their boundaries were.

The nature of boundary disputes and how they are resolved also provides clues to what is an appropriate boundary system, and there were a number of boundary disputes in Imizamo Yethu. Boundary disputes were examined in 21 resident interviews/group discussions. Stories of boundary disputes were recounted in 10 of these sessions. In describing the disputes, respondents said that in the case of an encroachment the injured parties went to the administrative office on the site. In the numerous government structural changes that have occurred since the demise of apartheid, this office has been staffed by officials from different local or provincial government structures and at one stage by an NGO's employees along with people from the community. In the case of a dispute, office staff came out to inspect and measure up the dimensions of the site. If necessary they then ordered the encroacher to move the structure to conform to the boundary monuments or dimensions. The author was aware of three instances where encroachers had refused to remove an offending structure. Two different respondents related a case of a shop where a community committee and the office staff had not been able to get the encroacher to move. One respondent said, 'The (community based) committee has not been able to get the shop owner to move. People are afraid of the man.' In another area of Imizamo Yethu, a respondent indicated that he had been stabbed by his neighbour in an argument over an encroachment, but he had still not been able to get the neighbour to remove the encroachment. In the third case, while the author was conducting interviews, the research team was approached by a woman who requested assistance in resolving a boundary dispute with her neighbour. In her case, the office staff had ordered her neighbour to remove an encroaching structure (part of a shebeen – or informal bar), but the neighbour refused to do so. The office staff were reluctant or powerless to enforce their decision and according to the respondent the staff had told the two parties to settle the dispute between themselves (Barry 1999).

Land grabbing does not explain all the encroachments observed in the aerial surveys, and the reason for the encroachment patterns were explored in some of the interviews. Encroachment by agreement also explains many of the encroachments observed.

The issue of contractual encroachment

was raised in nineteen interviews/group sessions. In nine sessions involving 17 people, participants indicated that they would allow a neighbour to encroach if, as mentioned above, 'there was an agreement allowing this'. In ten other sessions where the issue was explored which involved 15 people, the participants were emphatic that they would not enter into such a contract and would not allow encroachment under any circumstances.

In two individual interviews, one respondent said that if the neighbour was his friend he would allow the neighbour to encroach by agreement. When another respondent gave a similar answer, he was then asked where the boundary of his site would be in such a case. He replied that the pins were still the boundary;'that person is like my lodger and I can order the encroachment to be removed at any time'. In another interview, when asked why people would agree to encroachments, a group of one male and two females said, 'If you have no money to extend your shack, you can allow someone else to build over the boundary. They don't pay rent in this case, but one can enforce the (boundary demarcated by the) pins at any stage.' Another group quizzed on this issue comprised a male and his female neighbour. The male indicated that he would permit a negotiated encroachment, but if they had an argument, he would tell the neighbour to move.

The concept of an encroacher being a lodger is similar to notion of borrowing of land in the traditional land tenure system in many sub-Saharan African customary land tenure systems. For example, in the North Sotho tenure system, land can be borrowed indefinitely by one family from another for growing crops in return for services such as ploughing the lenders' fields. In exceptional cases, such as the lender dying without descendants, the borrowers could end up owning this land (Letsoalo 1987). A number of authors have observed that land tenure practices in urban informal settlements in sub-Saharan Africa often incorporate both customary and western practices (e.g. Durand-Lasserve and Clerc 1996). Contractual encroachment practices may possibly be an instance of these practices.

Finally, in one interview a woman expressed a belief about boundaries and encroachment which differed from the rest of the participants. She felt that the pins were not that important. She was happy if the boundary (fences) were in more or less the right place. It did not matter if fences were moved around a bit from time to time.

The issues of boundaries in Imizamo Yethu was revisited in interviews with officials, community leaders and a land surveyor between 2002 and 2005. Officials believed that most of the boundary monuments had disappeared and there had been numerous instances of encroachment and requiring people to move. Furthermore, as registration of ownership was taking place and formal structures were being constructed, construction could not proceed without a building inspector being able to ascertain if the building fell within the legally defined building lines. The boundary monuments were needed for this check to occur. Thus phases I and III were resurveyed in 2003 to relocate the boundary monuments.

There were significantly more original monuments in place than many of the participants in the study would have one believe. After the survey had been completed, the land surveyor estimated that between 50% and 60% of the original boundary monuments were still in place and he had replaced the missing ones. He could not recall observing monuments that had been moved. However, it is possible that cases where monuments had been moved had been addressed prior to the resurvey.

In 2005, an official noted that there were some five issues over buildings straddling boundaries. The City of Cape Town had chosen to adjust the cadastral boundaries rather than order the brick and mortar structures to be demolished. An official explained that the City had not been involved in administering Imizamo Yethu until 2000, and thus rather than enforce the removal of an encroaching structure they chose a softer approach – i.e. there was enough conflict between residents and the City already without forcing people to demolish parts of their homes.

CONCLUSIONS

The Imizamo Yethu case, along with a number of other cases studied in Cape Town, suggests that under conditions of high levels of conflict and competition for power and resources within a settlement then a system of fixed monuments surveyed to a high precision is appropriate. It allows the monuments to be relocated and possibly restored to a high precision in the event of a perceived number of disputes. The fierce reaction to unauthorised encroachment suggests that residents desired a high level of precision in the position of the monuments in the event of a dispute; but perhaps when faced with the reality of a minor, unintended encroachment people may relent and allow it.

No data emerged to support the notion of a mid-point system, nor a superblock system where in the latter case a community determines the positions of the internal boundaries. In the latter case, one was left with the impression that people desired an official, legal determination of their boundaries which they could defend on the basis of powers vested outside of community structures. The superblock system, using a communal title form, may yet be suitable as a long term strategy to ensure that cities remain compact. However, the Imizamo Yethu case suggests that in competitive, conflict ridden environments the internal layout should be determined by outsiders.

The Imizamo Yethu case tends to support Fourie's (1994) conjecture that general boundaries are unsuitable in high conflict situations. However, this may be challenged on the basis that general boundaries properly managed and policed may also have been suitable in Imizamo Yethu. My analysis of the situation is that the costs of involving outsiders in adjudicating disputes in a general boundary system may be significantly higher than getting a fixed boundary system resurveyed and then preventing any permanent structures from being erected unless they comply with building regulations.

In the Imizamo Yethu case perhaps more effort should have been made to protect the monuments or perhaps a durable material less attractive to scrap metal merchants should have been used. What has been found in other cases in the broader study is that it is good practice to measure up the site with the occupants when the site is handed over and at the same time compare the measurements with the cadastral plan. In this way, it is clear to all surrounding occupants if a monument has been moved and that if a monument is moved it is possible to detect this.

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IMPORTANT CONSIDERATIONS FOR CRANIOFACIAL MAPPING USING LASER SCANNERS

Zulkepli Majid (zulkepli@fksg.utm.my)
Universiti Teknologi Malaysia

Albert K. Chong (chonga@albers.otago.ac.nz)
University of Otago, New Zealand

Halim Setan (halim@fksg.utm.my)
Universiti Teknologi Malaysia

Abstract

The use of a laser scanning system for human craniofacial mapping has gained considerable interest recently as it offers a non-contact method which is very efficient in capturing a vast amount of accurate spatial data. Nonetheless, there is a need for a thorough evaluation to identify the important technical factors which may affect the accuracy of the system. This paper discusses the tests and the results of an evaluation of the Minolta VI-910 3D laser scanning system used to capture craniofacial surface data. The research shows that the factors to consider for craniofacial mapping are: scan distance, camera focal length, laser beam intensity, scanning resolution, convergence angle and number of overlapping scans.

Keywords: convergence angle, craniofacial mapping, focal length, laser scanner, scan beam intensity, scan resolution

Introduction

Research carried out by Kusnoto and Evans (2002), Da Silveira et al. (2003) and Boehnen and Flynn (2005) to study 3D laser scanning technology for capturing 3D craniofacial soft-tissue data to model human faces has highlighted the efficiency of the technology. In general, the Konica Minolta VI-910 laser scanner was regarded as the most accurate scanner for the task (Fig. 1). The quality of the detail of the scan is significantly higher than other scanners which have been tested and this is an important advantage for biometrics and biomedical mapping (Kau et al., 2004; Majid et al., 2004; Kovacs et al., 2006). A drawback of the Minolta VI-910 laser scanner was that it took about 19 s to perform an accurate scan. The amount of time was considered too long and could cause error due to the subject's facial movement during scanning. To reduce the possibility of movement occurring between set-ups (one set-up for the left face scan and one for the right face scan) for a complete scan, two Minolta VI-910 laser scanners were acquired and they would be used simultaneously in the Malaysian national craniofacial mapping project which requires a linear measurement accuracy of 0·7 mm between pairs of landmarks.

The scanner exploits a technique known as structured light triangulation (Majid et al., 2004). The surface of the object is illuminated with a red laser beam. Assuming that the light is

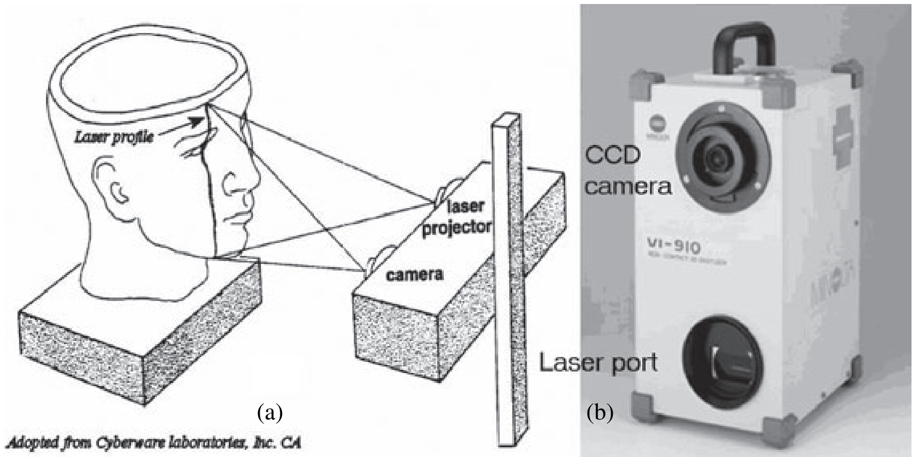

FIG. 1. Principle of laser scanner: (a) CCD camera and laser projector configuration; (b) Minolta VI-910.

projected in a single plane, a triangulation algorithm can determine the depth of the surface (Fig. 1(a)). Details of the mathematics can be obtained in Boyer and Kak (1987) and Sanderson et al. (1988). Generally, the system consists of a structured laser light source, a light projection system and a digital imaging system. The structured laser beam creates an ultra-thin profile on the object, which is photographed by a CCD camera mounted close to the projector. The relative position (a vector) between the internal reference point of the projection system and the camera lens is fixed. In addition, the angle of each projected laser profile plane and the angle of the camera optical axis are calibrated in advance. Subsequently, the x, y and z coordinates of the object-space position of each pixel on the object can be computed using the scale of the photography, the relative positional vector and the known angles. A least squares technique is used to compute a set of optimum 3D coordinates of the object surface.

This paper discusses the detail of the tests and results of studying the Minolta VI-910 laser scanner based on a few important technical factors considered to affect the accuracy for human craniofacial mapping. Details of each factor are provided in the sub-sections. The factors considered were as follows:

(1) scan distance (S_d) and camera focal length (f);
(2) scan resolution (R);
(3) scan intensity (I);
(4) number of overlapping scans per craniofacial area (N); and
(5) convergence angle (α).

It should be noted that these factors were studied separately. The interaction of these factors as a whole is beyond the scope of this study.

METHODOLOGY

Tests were carried out using a custom-built "bench-top-frame" device (Konica Minolta, Japan, Fig. 2). The VI-910 laser scanner was positioned as shown in the figure while the mannequin could be moved forward and/or backward using a sliding plate along a set of steel rails. Various scan distances could be set up for the test.

LOW RESOLUTION COLOUR FIG

FIG. 2. Set-up of the tests using a custom-built device.

Test 1: Optimal Scan Distance and Camera Focal Length

The objective of the study was to find the optimal scan distance (distance from laser scanner to the subject) for scanning the human craniofacial area. The study also investigated which of the available lenses is most suitable for this application. The Minolta VI-910 scanner provides three types of lens: namely, wide angle ($f = 8$ mm); medium angle ($f = 14$ mm); and telephoto ($f = 25$ mm). A range of scan distances was used: 700, 800, 900 and 1000 mm. The scan distances were based on the findings of previous work on human craniofacial mapping conducted by the authors (Majid et al., 2005). A minimum scan distance of 700 mm was needed to cover the scan area using the medium-angle lens. Only the wide-angle lens and medium-angle lens were used in the tests. The telephoto lens was not selected because it is generally used for scanning small objects, such as a dental cast, and then often at a very short scan distance. According to the manufacturer, the telephoto lens could be used to scan a bigger object, but that would require long scan distances (>1000 mm) to obtain optimal coverage of the craniofacial area.

To mimic a human craniofacial object, a mannequin was marked with 1·5 mm diameter black circular dots representing craniofacial landmarks. Accordingly, the dot would return a 34-pixel sample at high and medium scanning resolution and an 8-pixel sample at low scanning resolution. Three sets of scans were performed for each scan distance, and for each set the mannequin was rotated 45° to the left and right as well as facing straight ahead (0°), so that a complete model of the craniofacial area could be obtained (Fig. 3). Subsequently, three sets of the 3D surface model of the mannequin were generated by precise registration and the merging process of each set of three scans using Rapidform 2004 software (version: PP2, INUS Technology, Seoul, South Korea). The software uses a set of proprietary algorithms in

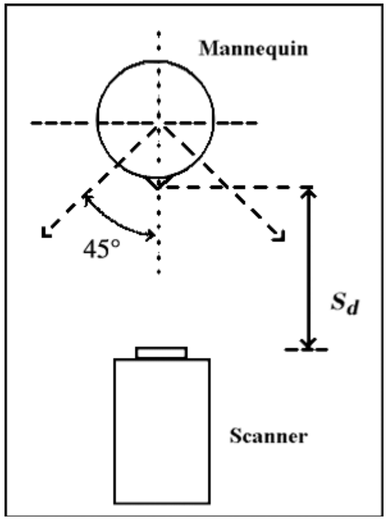

FIG. 3. Set-up of the scan distance test. Note that S_d is scan distance.

the merging process (including target centre determination), however, the authors believe that comparable techniques can be found in Haar et al. (2005). The registration and merging process of the software is as follows:

(a) Initial Registration. The initial registration roughly registers one scan (shell) with another overlapping one using geometric features on two scans (shells). Common geometric features, also known as corresponding points, are selected by the user. The accuracy of the initial registration was based on the accuracy of pairs of the corresponding points selected by the user. The more accurately the corresponding points are located, the better the registration result. For good accuracy, the number of selected pairs of corresponding points is between five and eight.

(b) Fine Registration and Merging Process. The fine registration process matches the overlapped regions of all the selected shells (in this case there are two: left scan from left scanner and right scan from right scanner). The merging process combines the data of the overlapping areas into a single point set. After merging, the difference between the data-sets is displayed as shell–shell deviation. The deviations between the surfaces were computed by using the normal from one of the surfaces to the other.

Consequently, the shell–shell deviation technique is an analysis of the quality of the registration of two adjacent overlapping scans. The technique may be used to evaluate the closeness of fit of two similar 3D surfaces (obtained from different viewpoints or different epochs) of the same object.

Slope distances (the shortest distance between two points in space) between the landmarks were measured using the “point to point measure” function of the same software. These distances were compared to the slope distance obtained by the Microscribe 3D digitiser system, which has a reported accuracy of 0·23 mm (Immersion Corporation, San José, CA, USA). The calibration of the Microscribe digitiser is not discussed in this paper, however, detailed information may be found from many sources such as Farag and Eid (2003) and Autodessys Inc. (2004).

Test 2: Laser Intensity

The maximum power of the laser was considered eye-safe by the manufacturer. The intensity of the scan beam can be set to auto mode or the user can adjust the beam manually. The main concern was the effect of the beam's intensity on the accuracy of the scanned data. By observing the laser beam of various intensities (numerical value on display) the "blooming" effect of the beam can be seen (Atkinson, 1996). A higher beam intensity causes higher backscattering, resulting in the phenomenon of blooming. Consequently, the beam intensity may have adverse effects on the texture and accuracy of the captured 3D spatial data. The test was designed to determine the optimal intensity of the laser beam required to obtain high quality data (spatial and texture) of the craniofacial surface. A mannequin textured so as to resemble human skin was selected for the test. The mannequin was scanned at various laser intensity values as shown in Fig. 4. All scans of this test were conducted at the same scan distance. The optimum scan distance obtained in Test 1 was used here. Similar to the previous test, the slope distances obtained from the test were compared with the distances gained from the Microscribe 3D digitiser system.

Test 3: Scanning Resolution

The Minolta VI-910 3D digitiser provides three classes of scanning resolution, namely: (1) low resolution (fast mode); (2) medium resolution (fine mode with one scan); and (3) high resolution (fine mode with three repeated scans). These scanning modes produce a different density of 3D point clouds and a different texture resolution. Tests were carried out using the three scanning modes to scan the craniofacial area of the mannequin and the process was repeated twice to ensure high quality data was captured for analysis. More details of the characteristics of point cloud intensity and the texture difference for the three scan resolutions are provided in the results and analyses section.

Test 4: Number of Overlapping Scans for the Craniofacial Area

The purpose of the test was to determine the optimal number of overlapping scans required to obtain a high quality complete 3D surface model of the craniofacial area. In general, a complete 3D model of the craniofacial area covers the surface from the left ear to the right ear and from the hairline to the bottom part of the chin. To obtain a complete surface model of the craniofacial area, the number of overlapping scans was considered an important

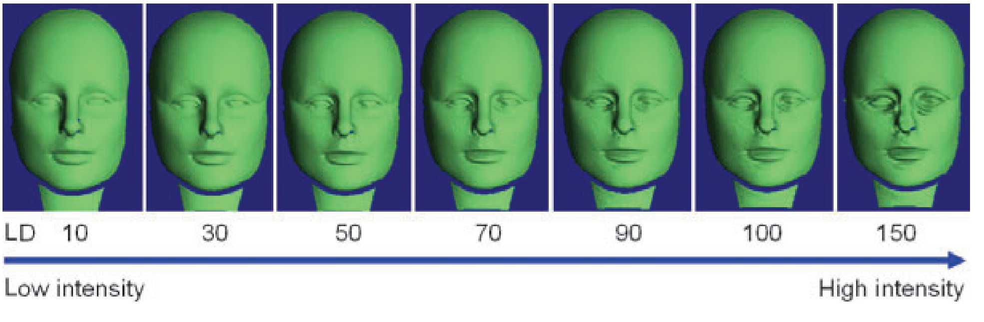

FIG. 4. Laser intensity in numerical values. Note the level of shading just below the right eye as laser intensity increases.

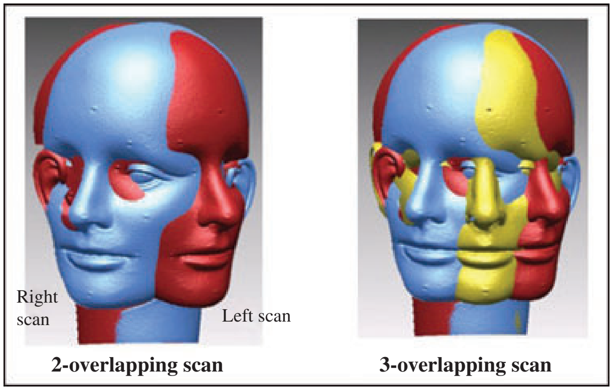

FIG. 5. Two and three overlapping scan configurations.

factor for both efficiency and accuracy. The test involved the acquisition of two sets of scans as described below (Fig. 5):

(1) three overlapping scans: the front view, the left and the right views of the mannequin;
(2) two overlapping scans: the left and the right views of the mannequin.

Overlapping scans were registered and merged to obtain a complete surface of the craniofacial area using Rapidform software (PP2). The evaluation of the test involved the measurements between craniofacial landmarks, marked as black dots on the mannequin. The slope distances obtained from the test were compared with the distances gained from the Microscribe 3D digitiser system.

Test 5: Convergence Angle

The test determined the optimal convergence angle (α) for setting the scanners to capture the craniofacial area (Fig. 6). The convergence angle is defined as twice ($2\times$) the angle

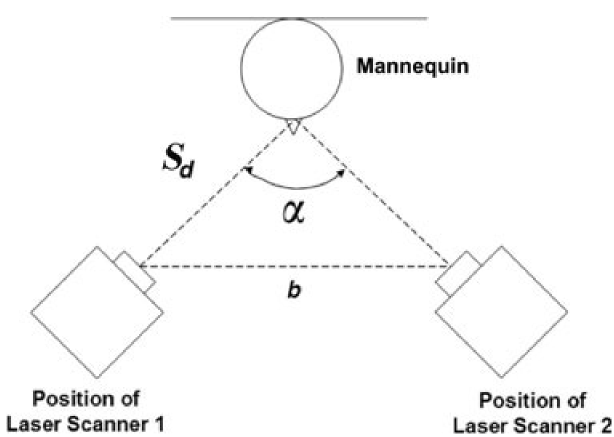

FIG. 6. The set-up for evaluating the convergence angle (α).

subtended between the vertical plane bisecting the head along the nose and the optical axis of the scanner camera lens. A set of convergence angles ranging from 20° to 140° at 20° intervals was used. In addition, the scan distance was fixed at 700 mm (based on previous test results of Test 1). Also, the aim of the study was to determine the optical geometry of the camera which would give the best results when two scanners were used together. The optical geometry could be a representation of the base (b) and S_d or α as shown in Fig. 6.

The scans from both scanners for each test angle were registered and merged using the Rapidform software. Again, slope distances of the landmarks were compared to the "true" slope distance. In addition, the accuracy of the merged data captured at each convergence angle was evaluated using the shell–shell deviation method.

Results and Analyses

Test 1: Optimal Scan Distance and Camera Focal Length

The slope distances between selected landmarks were determined by the Microscribe 3D digitiser system and the average of five sets was used as the "true" slope distance (Fig. 7). The same slope distances measured on the 3D craniofacial surface model were compared with the "true value".

Tables I and II show the results of the medium-angle lens and the wide-angle lens tests, respectively. The scan distances (S_d in mm) are shown at the top of the tables and all measurements are in millimetres. Only seven important slope distances were selected from a set of several hundred combinations. They are the distances normally required for anthropometric study.

The difference between the measurement of the Microscribe 3D digitiser and the wide-angle measurements shown in Table II are positive, indicating the possibility of a bias or scale error. Further analysis shows that the values are within the manufacturers' specifications for both systems and hence no further analysis was carried out on the results. In the context of this paper, the standard deviation is more important than the mean error as the project specifications

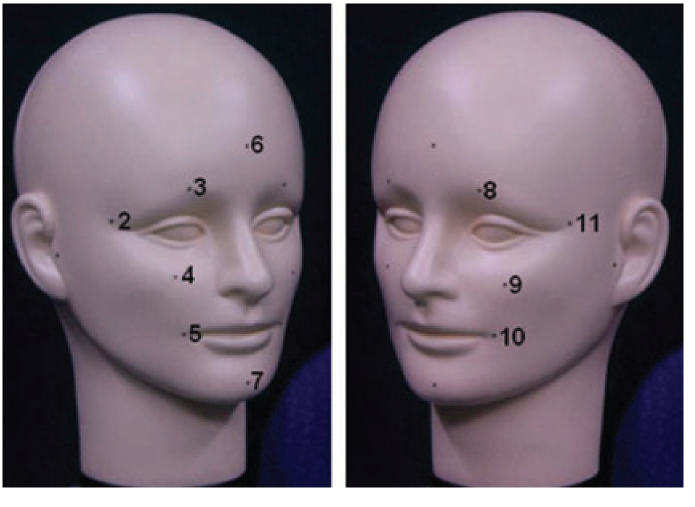

Fig. 7. The location of the anthropometric marks discussed in the paper.

Table I. Slope distance comparison of the medium-angle lens measurement of various scan distances. Note that the true values and the measurements are in the Appendix.

From–To	$S_d = 700$	$S_d = 800$	$S_d = 900$	$S_d = 1000$
3–8	−0·063	−0·011	0·642	0·514
4–9	−0·249	0·825	0·978	0·83
5–10	−0·084	−0·309	1·186	0·238
6–7	0·112	0·709	1·57	0·904
3–4	−0·019	0·64	0·422	0·283
8–9	−0·12	0·569	0·677	0·411
2–11	−0·388	0·548	2·205	2·193
Mean	−0·116	0·424	1·097	0·768
Standard deviation	0·162	0·419	0·621	0·678

Table II. Slope distance comparison of the wide-angle lens measurement of various scan distances.

From–To	$S_d = 700$	$S_d = 800$	$S_d = 900$	$S_d = 1000$
3–8	1·632	1·554	0·871	1·082
4–9	2·501	1·645	1·613	1·541
5–10	2·076	1·618	1·458	1·027
6–7	4·075	3·64	2·948	3·042
3–4	2·115	1·629	1·687	1·695
8–9	1·6	0·995	1·537	1·54
2–11	4·116	3·854	3·716	2·44
Mean	2·588	2·134	1·976	1·767
Standard deviation	1·075	1·127	0·989	0·731

provide for the value of measurement standard deviation. Further analyses are provided in the discussion section.

In general the results show that the medium-angle lens gives the best values for all scan distances tested. Nevertheless, the results also show that the accuracy reduces as the scan distance increases.

Test 2: Laser Intensity

Fig. 8 shows: (a) the true shape and colour of the mannequin's right eye (picture taken by a digital camera); and (b) the surface shown in (a) darkens as the beam intensity increases. Fig. 9 shows: (a) the shape of the nose worsens as the intensity increases; (b) the amount of shape change between intensity value of 20 to intensity value of 220; and (c) the shape change in (b) as depicted by the grid mesh. In short, the figure shows that adjusting the beam intensity manually could introduce large errors in the scan. Consequently, the use of the manual setting should be carried out with caution. The Minolta VI-910 3D laser scanner is an intelligent scanner; a built-in sensor determines the optimal laser intensity required at a set scan distance. Fig. 10 shows the error in the shell–shell deviation between a surface model scanned at the optimal laser intensity (around 20 to 40) and one scanned at an intensity of 150. Fig. 11 shows the average shell–shell rms deviation versus the laser intensity. In addition, Table III shows a sample of the results of slope distance comparisons. They are: (1) scan at intensity value 20; (2) scan at intensity value 100; and (3) scan at intensity value 150. More discussion can be found in the discussion section of this paper.

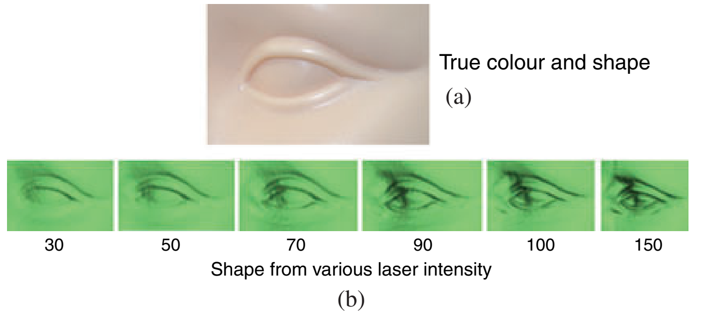

FIG. 8. Texture quality versus laser beam intensity: (a) true colour; (b) shape obscured due to increased beam intensity.

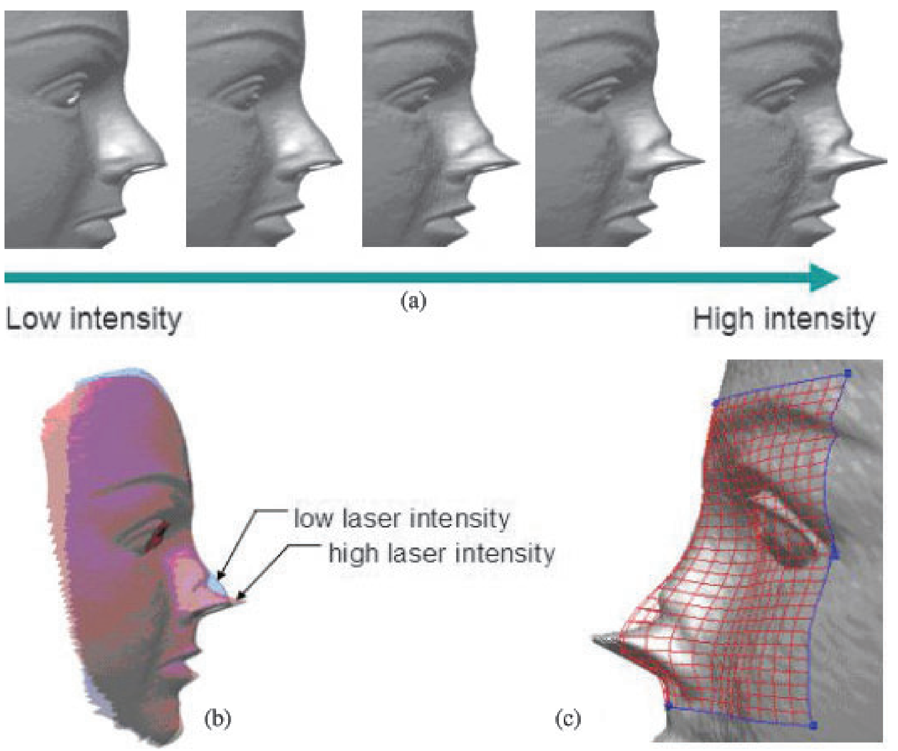

FIG. 9. Scan error versus beam intensity: (a) shape change based on intensity; (b) surface shape change introduced; (c) the shape change of (b) as depicted by a grid mesh.

Test 3: Scanning Resolution

The shell–shell deviation analysis was carried out to find the maximum deviation value between (a) low–high resolution data-sets and (b) medium–high resolution data-sets. The results of the study are presented in Table IV.

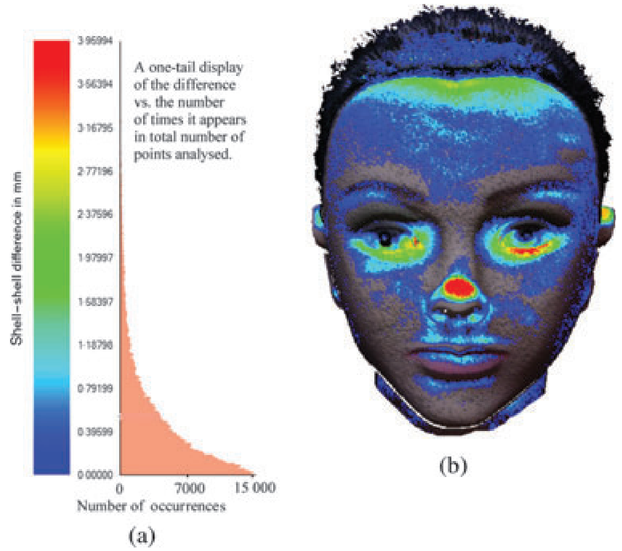

Fig. 10. Shell–shell deviation analysis: (a) a normal distribution of shell–shell difference in mm; (b) the location of large differences as depicted by bright colours.

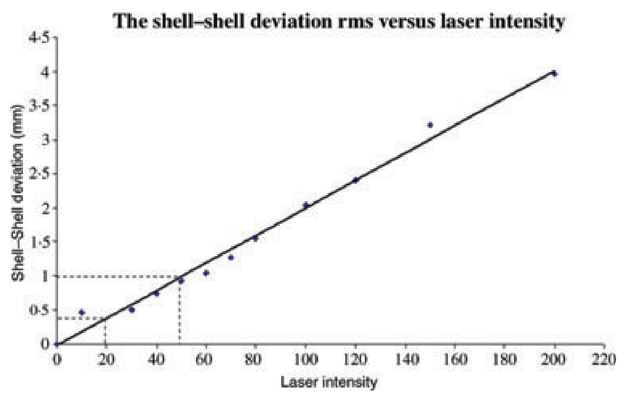

Fig. 11. A graph showing the averaged shell–shell rms deviation versus the laser intensity value. Note that the optimal intensity lies between the dotted lines.

Table III. A sample of the slope distance comparison of the beam intensity test results.

From–To	*At I = 20 (mm)*	*At I = 100 (mm)*	*At I = 150 (mm)*
3–8	−0·202	−0·327	−0·341
4–9	0·056	0·239	−0·459
5–10	0·005	0·279	−0·246
6–7	0·552	2·973	2·406
3–4	−0·09	1·216	1·247
8–9	−0·012	0·191	0·871
2–11	0·589	1·025	1·003
Mean	0·128	0·799	0·640
Std Dev	0·290	1·012	0·973

TABLE IV. Shell–shell deviation analysis of scanning resolution.

Resolution Test	*Maximum Deviation (mm)*	*Average Deviation (mm)*	*Standard Deviation (mm)*
Low–High	1·065	0·446	0·215
Medium–High	0·349	0·040	0·047

The table shows that the scanning resolutions suitable for the craniofacial surface are the high and medium resolutions with maximum shell–shell deviation of 0·349 mm compared to low resolution of 1·065. Additionally, the test results show that both high and medium resolution scans have a similar point density of 576 per square inch (0·044 mm pixel^{-1}), however, the low resolution produces only 144 per square inch. Fig. 12 shows the distribution of points in the point cloud. Table V shows the results of slope distance comparison and the standard deviation indicates that both medium and high resolution scans are suitable for this project.

Test 4: Number of Overlapping Scans Needed for the Craniofacial Area

The results of the slope distance comparison between the "true", two-scan and three-scan configuration shows that the best measurement belongs to the three-scan configuration (Table VI). However, the two-scan configuration gave a standard deviation of 0·632 mm which satisfies the landmark measurement accuracy of 0·7 mm for this craniofacial project. In general, a three-scan configuration would require the use of three scanners as head movement could produce large errors in the data-set when all three scans were not carried out simultaneously.

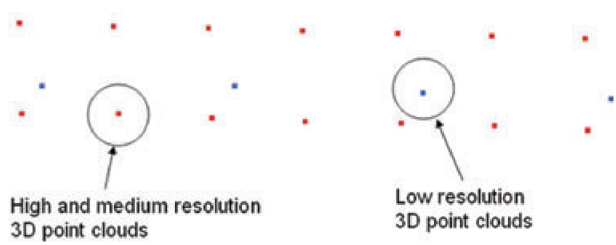

FIG. 12. Point cloud density based on scanning resolution.

TABLE V. Slope distance comparison of the scanning resolution test.

From–To	*Low Resolution (mm)*	*Medium Resolution (mm)*	*High Resolution (mm)*
3–8	−0·553	−0·727	−0·515
4–9	−0·052	−0·104	0·168
5–10	−0·322	−0·586	−0·658
6–7	2·318	0·168	−0·176
3–4	1·195	0·464	0·767
8–9	1·023	0·261	0·692
2–11	0·444	0·731	0·973
Mean	0·579	0·03	0·179
Std Dev	0·934	0·496	0·603

TABLE VI. Slope distance comparison between the ‘true’ value, 2-scan and 3-scan measurement.

From-To	*True value (mm) (A)*	*2 scans test (mm) (B)*	*3 scans test (mm) (C)*	*B-A*	*C-A*
3–8	52·959	52·867	52·939	−0·092	−0·02
4–9	61·387	61·040	61·551	−0·347	0·164
5–10	57·745	57·150	57·672	−0·595	−0·073
6–7	115·239	115·826	115·577	0·587	0·338
3–4	46·573	47·192	47·196	0·619	0·623
8–9	47·705	48·202	48·143	0·497	0·438
2–11	112·505	113·547	113·483	1·042	0·978
			Mean	0·244	0·349
			Std Dev	0·551	0·344

Test 5: Convergence Angle

In the data analysis, slope distances between landmarks were compared to the “true” value. In addition, the registration accuracy of each convergence angle was evaluated using the shell-to-shell deviation method.

Fig. 13 shows the size of the overlapping area in relationship to the convergence angle and Table VII shows the approximate percentage of overlap over the craniofacial area. In Fig. 14 it can be seen that the shell–shell deviation error at the 90° convergence angle is smaller, compared to other convergence angles. The test also involved larger convergence

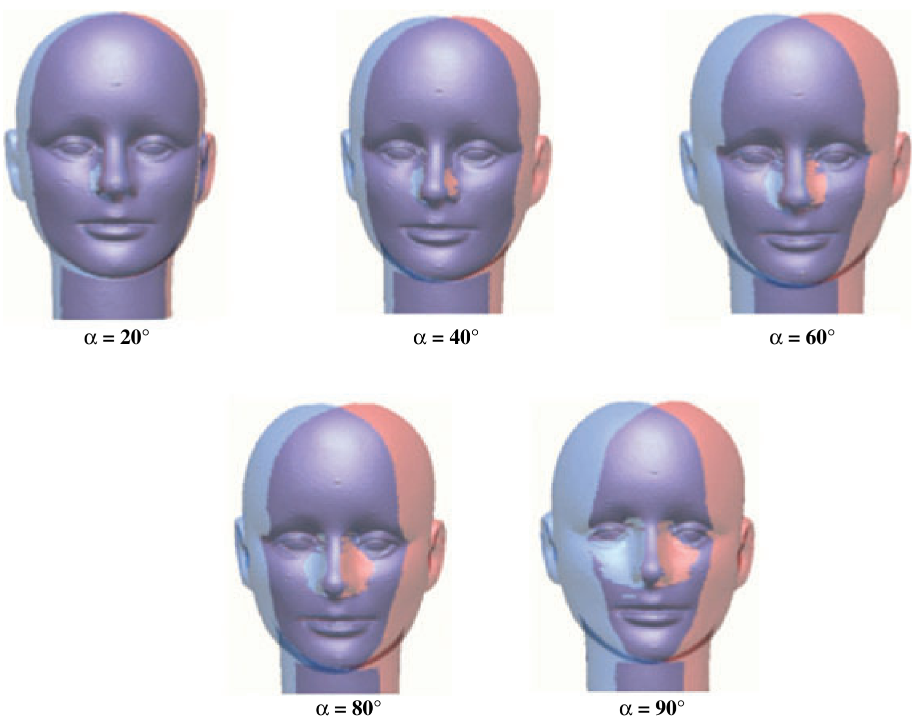

FIG. 13. The effect of the convergence angle on the corresponding overlapping area.

TABLE VII. Approximate percentage of overlap of the figure shown in Fig. 13.

Convergence angle	*α = 20*	*α = 40*	*α = 60*	*α = 80*	*α = 90*
Percentage (%)	89	85	81	77	72

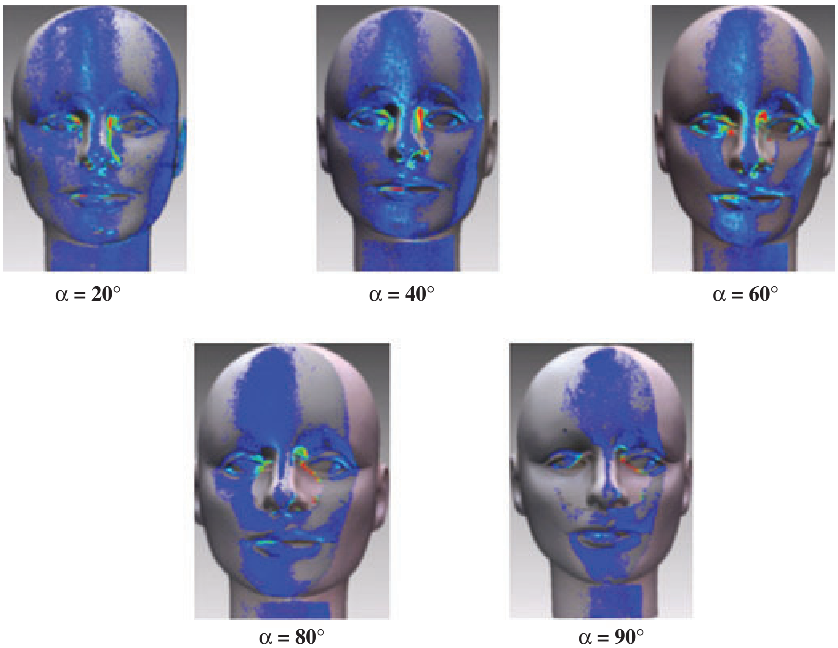

FIG. 14. Shell–shell deviation analysis of the convergence angle test. Note that the colour chart used is similar to that in Fig. 10.

angles (120° and 140°); however, the registration failed (Fig. 15) because of the limited number of available corresponding features to perform high quality registration (Fig. 16).

The test on the optimal convergence angle was evaluated by analysing completeness of the 3D model that covered the craniofacial area (from the left ear to the right ear, from the hairline to the bottom of the chin). Fig. 17 shows the effect of the convergence angle on the shape of the modelled mannequin's ear. The figure shows clearly that the shape of the inner loop of the modelled ear becomes smoother as the angle increases. It seems that the closer the convergence angle is to the normal to the plane of the ear the more accurate the scan data which could be obtained. More information is provided in the discussion section. Table VIII shows the results of the slope distance comparison of the convergence angle test. The standard deviation obtained for the convergence angles 60°, 80° and 90° satisfy the project accuracy requirement.

DISCUSSION

Accuracy Factor

Generally, for a typical single scan the accuracy of the 3D points is comparable to the value provided by the manufacturer. In this study of craniofacial mapping, initial tests showed

LOW RESOLUTION COLOUR FIG

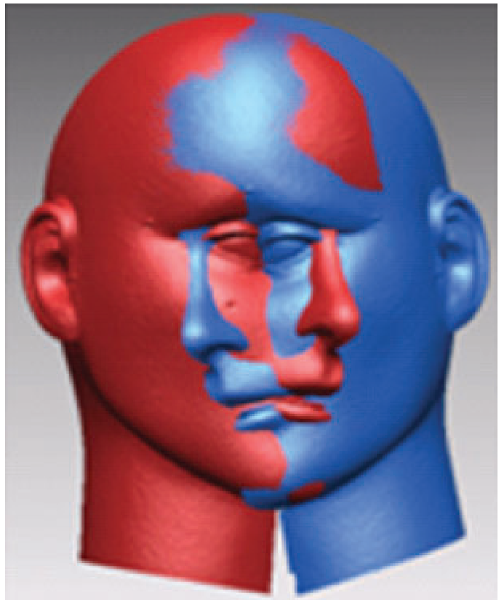

FIG. 15. Errors in the registration of the left and right scans of the 120° convergence angle.

LOW RESOLUTION COLOUR FIG

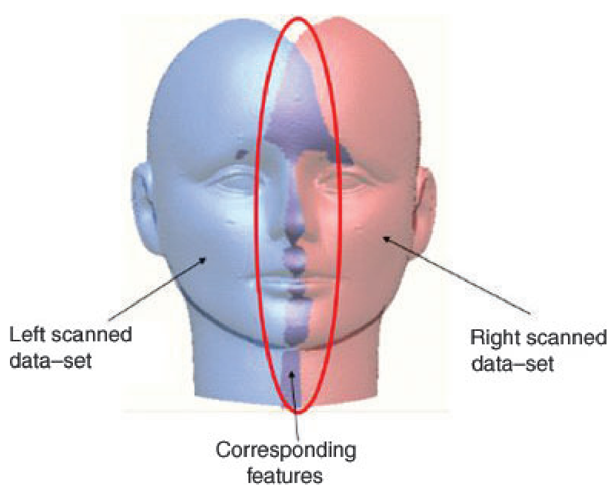

FIG. 16. Limited number of corresponding features to perform accurate 3D registration of the two overlapping scans.

that there might be factors which could influence the quality of the captured data. Consequently, it was apparent that the accuracy of the laser scanning system for craniofacial mapping is a function of several parameters such as scan distance, focal length of lens, scanning resolution, laser beam intensity and the number of scans. Equation (1) expresses the

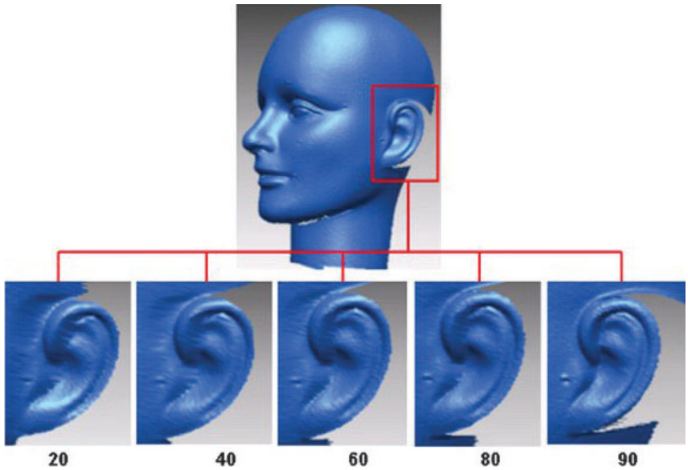

FIG. 17. Effect of the convergence angle to the modelled ear.

TABLE VIII. Slope distance comparison of the convergence angle test. Note that only the differences are presented.

From–To	*α = 20° (mm)*	*α = 40° (mm)*	*α = 60° (mm)*	*α = 80° (mm)*	*α = 90° (mm)*	*α = 120° (mm)*
3–8	−0·645	−0·747	−0·724	−0·532	−0·542	−0·297
4–9	−0·042	−0·474	0·107	0	−0·436	0·13
5–10	−0·431	−0·233	−0·636	0·251	0·619	−0·365
6–7	−0·82	−0·138	−0·384	−0·556	−0·017	−1·97
3–4	−0·035	−0·592	−0·472	−0·177	−0·197	−0·339
8–9	−0·571	−0·602	−0·213	−0·058	0·406	−0·024
2–11	−1·381	−1·361	−1·033	−1·433	−1·411	−1·514
Mean	−0·561	−0·592	−0·387	−0·358	−0·225	−0·626
Std dev	0·433	0·371	0·276	0·514	0·621	0·736

loose correlation between the parameters. A study to find the mathematical correlation was not the objective of the research.

$$\sigma_{xyz} = (\alpha, I, N, f, S_d, R) \qquad (1)$$

where

σ_{xyz} = 3D point standard error
α = convergence angle
I = laser beam intensity
N = number of scans per craniofacial area
f = focal length of the lens
S_d = scan distance, and
R = scan resolution.

Optimal Scan Distance and Camera Focal Length

Using a scan distance of 700 mm and the medium-angle lens has provided consistent accuracy for hundreds of scans of adult samples. However, it must be noted that the test results were based on craniofacial areas of adult size. The craniofacial project in the future also calls for the mapping of infant samples. Consequently, more tests will have to be carried out on the much smaller craniofacial area of infants.

Laser Beam Intensity Test

As discussed elsewhere, higher beam intensity causes higher backscattering which appears as a blooming phenomenon. Subsequently, it was determined that the beam intensity has an adverse effect on the texture and accuracy of the captured 3D spatial data. A limited number of intensity values was selected for the comprehensive test (Table III). The reason was that a preliminary test based on 11 intensity values shows that the average shell–shell rms deviations—which satisfy the project accuracy requirement—were with the 20 to 40 bands. Nevertheless, no rigorous slope distance comparisons were carried out for these preliminary tests. Consequently, a comprehensive test for three intensity values (20, 100 and 150) was needed to confirm that the preliminary test result of using shell–shell deviation analysis was acceptable.

As a result of this test only the auto mode was used for the data capture and room lighting was maintained similar to that when the test was carried out.

Convergence Angle

With the limited number of convergence angles selected for the test it was difficult to pinpoint the optimal convergence angle within 5 degrees. The shell–shell deviation error size shows that a 90° angle gave the lowest average error (Fig. 15). Slope distance comparison showed the lowest mean was at 90° and the lowest standard deviation was at 60° (Table VIII). As both standard deviations satisfy the project requirement the lowest mean was selected as a better configuration. However, the texture and the shape for the ear were most comprehensible at 90°. This is an important feature for craniofacial mapping (Fig. 17). Based on the pixel size of 0·044 mm a difference of 0·073 mm in the standard deviation between 60° and 90° is obviously not large in terms of pixels. In other words, it is easy to miss 2 pixels in digitising the anthropometric mark. In addition, it is difficult to set the angle precisely for a regular hospital environment where patients' positions could be less than ideal. Consequently, it is believed a convergence angle of between 80° and 90° would be ideal.

Scan Resolution

It appears that the high and medium resolution scans produce similar measurement accuracy in this study. As mentioned elsewhere in the paper, the high resolution scan requires more time because it requires three-repeated scans. Consequently, only the medium scan was used and thus far no error has been discovered in the work.

Live Face

Two other issues are worth a brief discussion: (1) facial hair and (2) facial movement. The scanner failed to capture data from facial areas which have a thick dark/black beard or a moustache. Generally, facial movement was not a problem with adult subjects. It became problematic when young children were involved as the left and right scans failed to merge accurately. As much as 25% of the work done on children required rescans.

Conclusions

Based on a preliminary study it was found that there could be a few important technical factors which could reduce the accuracy of captured laser scan data. Consequently, these factors were studied in more detail and the results show that accuracy could be degraded considerably. A more comprehensive study, though desirable, would have been significantly more time-consuming.

The findings show that the following parameters are optimal for the factors discussed:

(1) Scan distance: 700 mm ± 100 mm.
(2) Optimum lens: the medium-angle lens.
(3) Laser beam intensity: auto mode or set the value to between 20 and 40 at normal room lighting.
(4) Convergence angle: 60° to 90°—best at 90°.
(5) Scan resolution: medium resolution.

The mathematical correlation between the factors and the accuracy of the spatial data was not evaluated. Looking at equation (1), it is easy to see that the scale (S_d/f) is an important factor as well as the resolution (R). Other factors, such as laser intensity and the number of scans per craniofacial area, are rather flexible; the first is sensor-controlled and the second is limited by the number of scanners. The latter is an important factor for reducing facial movement during scanning, particularly of children. Also, dark or black facial hair is a problem. Tests carried out in various lighting conditions (from poor lighting to a brightly lit room) show that the scanner performs accurately in all conditions.

By and large, the study was useful because the knowledge gained was important in an endeavour to obtain high quality results. Based on the test results it was possible to achieve the project accuracy specification for the data captured.

Further research could include an intelligent system that automatically displays the achievable accuracy based on the lens used, the scan distance, the scan resolution and other necessary data.

Acknowledgement

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Appendix

Table AI. The true slope distance and slope measurements of the medium-angle lens measurement of various scan distances.

From-To	*True value*	$S_d = 700$ mm	$S_d = 800$ mm	$S_d = 900$ mm	$S_d = 1000$ mm
3–8	52.959	52.896	52.948	53.601	53.473
4–9	61.387	61.138	62.212	62.365	62.217
5–10	57.745	57.661	57.436	58.931	57.983
6–7	115.239	115.351	115.948	116.809	116.143
3–4	46.573	46.554	47.213	46.995	46.856
8–9	47.705	47.585	48.274	48.382	48.116
2–11	112.505	112.117	113.053	114.710	114.698

Table AII. The true slope distance and slope measurements of the wide-angle lens measurement of various scan distances.

From-To	True value (A)	$S_d = 700$ mm	$S_d = 800$ mm	$S_d = 900$ mm	$S_d = 1000$ mm
3–8	52.959	54.591	54.513	53.830	54.041
4–9	61.387	63.888	63.032	63.000	62.928
5–10	57.745	59.821	59.363	59.203	58.772
6–7	115.239	119.314	118.879	118.187	118.281
3–4	46.573	48.688	48.202	48.260	48.268
8–9	47.705	49.305	48.700	49.242	49.245
2–11	112.505	116.621	116.359	116.221	114.945

Résumé

Zusammenfassung

Die Anwendung eines Laserscanningsystems zur Erfassung menschlicher Gesichtszüge hat großes Interesse hervorgerufen, da mit dieser berührungslosen Messmethode sehr effizient große Datenmengen hoher Genauigkeit erfasst werden können. Trotzdem muss zunächst eine durchgreifende Analyse durchgeführt werden, um die wichtigen technischen Faktoren zu erfassen, die die Genauigkeit des Systems beeinflussen können. Dieser Beitrag stellt dazu die Versuche und Ergebnisse eines Minolta VI-910 3D Laserscanningsystems vor, mit dem menschliche Gesichtsoberflächen erfasst worden sind. Folgende Faktoren sind demnach zu berücksichtigen: Scan-Entfernung, Brennweite der Kamera, Intensität des Laserstrahls, Scan-Auflösung, Konvergenzwinkel und Anzahl überlappender Scans.

Resumen

La utilización de sistemas de escáner láser para el cartografiado craneofacial en personas ha recibido mucha atención recientemente ya que es un método sin contacto muy eficiente para obtener una gran cantidad de datos espaciales exactos. Sin embargo, es necesario realizar una evaluación minuciosa para identificar los factores técnicos importantes que pueden afectar a la exactitud del sistema. Este artículo examina las pruebas y resultados de una evaluación del sistema de escáner láser tridimensional Minolta VI-910 en la obtención de datos de la superficie craneofacial. La investigación señala que los factores a considerar en el cartografiado craneofacial son: la distancia de escaneado, la distancia focal de la cámara, la intensidad del haz láser, la resolución de escaneado, el ángulo de convergencia y el número de escaneos con solape.

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ORIGINAL ARTICLE

Natural Features Technique for Non-Contact Three Dimensional Craniofacial Anthropometry Using Stereophotogrammetry

Z. Majid[1*], A. Chong[2], H. Setan[1], A. Ahmad[1], Z.A. Rajion[3]

[1]Faculty of Geoinformation Science & Engineering, Universiti Teknologi Malaysia, [2]School of Surveying, University of Otago, Dunedin, New Zealand, [3]School of Dental Sciences, Universiti Sains Malaysia, Kubang Kerian, Kelantan
*Corresponding author: zulkepli@fksg.utm.my

ABSTRACT
This paper describes the use of stereophotogrammetry approach to measure and hence identify accurately three-dimensional (3D) coordinates of important landmarks on a craniofacial surface. A “novel” technique dubbed as “natural features” technique was employed to accurately compute the 3D coordinates of selected craniofacial landmarks. The natural features technique involves the use of 3D coordinates of the natural features (such as acne, scar, corners of eyes, edge of mouth, point of chin, etc.) that appear on the craniofacial surface as an absolute stereophotogrammetric mapping control points. The 3D coordinates of the natural features were gained using digital photogrammetric bundle adjustment method. Validation of the proposed technique has firstly been carried out using mannequin and finally, it was applied on the real-life human faces. The result shows that the craniofacial landmark measurement accuracy of 0.8mm with one standard deviation can be successfully achieved by the proposed technique.

Key words: stereophotogrammetry, craniofacial landmarks, 3D coordinates

INTRODUCTION

Craniofacial anthropometric measurements required high quality measuring tools in order to get the highest possible measurement accuracy (Farkas *et al.*, 1996). Among the methods used, stereophotogrammetry was promised to be familiar as a non-contact, non-invasive, reproducible, fast, high-accuracy, practical and cost-effective for measurement of facial morphology (Naftel *et al.*, 2004; Burke *et al.*, 1983; Hay *et al.*, 1985; Majid *et al.*, 2005; Meintjes *et al.*, 2002; Ras *et al.*, 1995; Wagner *et al.*, 2005; Johnston *et al.*, 2003).

Generally, photogrammetric control frame with targets (generally known as control frame technique) is required for the stereo orientation of the craniofacial stereo-photographs. The control is needed to allow scaling and orientation of the spatial model during the later analysis (Newton, 1974). The control frame may be placed over the patient’s head (Savara and George, 1984); near both side of the head (Peterson, 1993) and in Schewe and Ifert (2000) the control frame were placed on a helmet. These three designs almost certainly covered in all published photogrammetric control configurations (Majid *et al.*, 2005). However, tests show that the recommended location of the targets on the control frame was not suitable for high accuracy stereo-orientation. The accuracy in the Z (along the optical axis) does not satisfy the project requirement of 0.7 mm. It becomes clear that the targets are too far from the facial surface. The problem can be solved by using natural features technique which involved the used of natural features such birth mark, acne or scar as photogrammetric control for the stereo orientation of the craniofacial stereo-photographs. In certain cases, the natural features may be tattooed on the object for the duration of the investigation (Newton, 1974).

A method was developed to obtain high accuracy 3D coordinate of the natural features. It involves a photogrammetric bundle adjustment of photographs from the three stereo-cameras using the photogrammetric control frame targets. The photogrammetric bundle adjustment computes the 3D coordinate of the natural features. Subsequently, the 3D coordinates of the natural features are used to carry out absolute orientation process of the craniofacial stereo-models.

METHODS

Setup of stereophotogrammetric system

The design of the photography is based on three stereo-pairs of photograph. Six Sony CyberShot F828 digital cameras were set up 600 mm from the object to capture the stereo images. The cameras were electronically synchronized using a LANC Shepherd controller (Figure 1).

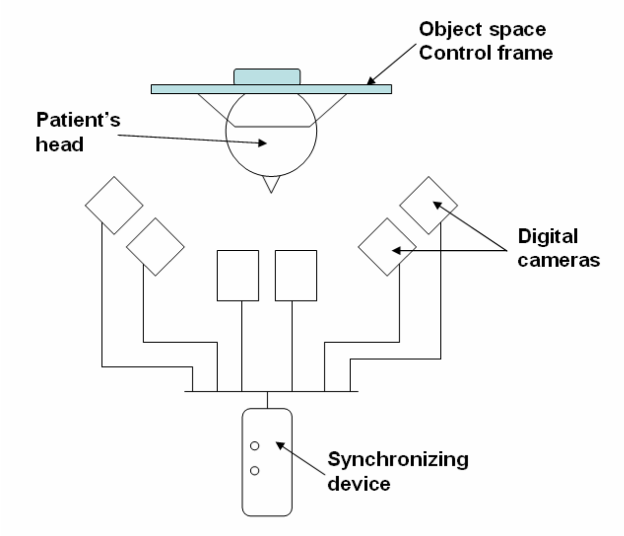

Figure 1 Stereo-photographic system used in the study

Individual camera was calibrated independently using a three-dimensional calibration device (Chong and Scarfe, 2000; Majid et al., 2005). The device consists of a camera mount and a three-dimensional (3D) test field. Retro-targets are placed in row and column as shown in Figure 2.

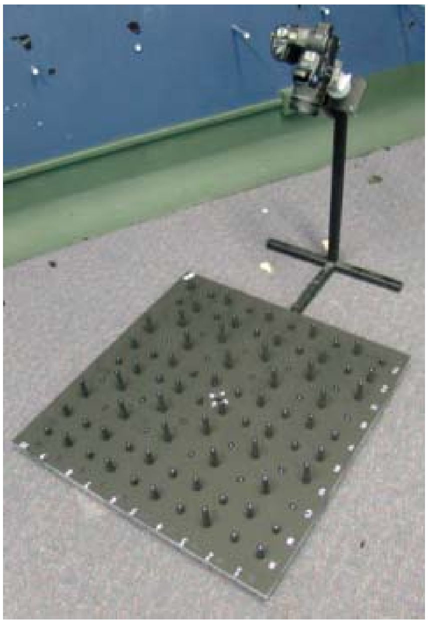

Figure 2 Three-dimensional camera calibration device

A photogrammetric control frame was built to provide an accurate 3D control for the research (Figure 3). Retro-targets were used to highlight the control points. The photogrammetric control frame also requires accurate calibration. The x, y and z coordinates of the targets were determined using convergent photographs and a bundle adjustment (Chong and Strafford, 2002). The coordinates would be used for the absolute orientation of the stereo models and for computing natural features 3D coordinates.

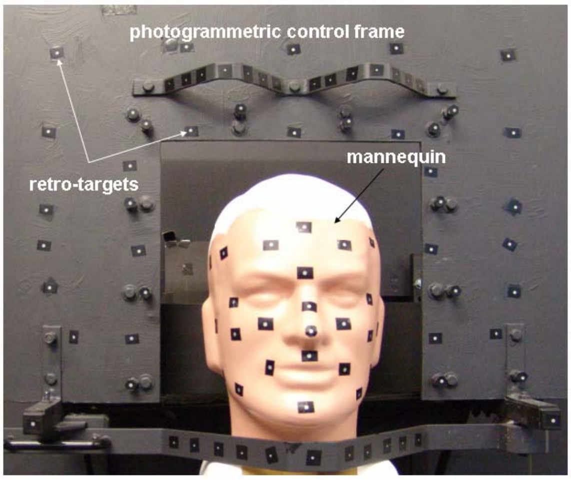

Figure 3 The photogrammetric control frame

Data collection

The data collection involved with photography process of the test objects. Two test objects involved in the research, the mannequin with retro-targets to represent the simulated natural features and real-life human faces. The photography process consists of four stages: (a) a convergent photography of the mannequin to capture a set of convergent photographs for the determination of 3D coordinates of the simulated natural features, (b) a stereo photography to capture a set of stereo-photographs of the mannequin for stereo-digitizing of the simulated natural features (c) a stereo photography to capture a set of stereo-photographs of real-life human faces with retro-targets and (d) a stereo photography to capture a set of stereo-photographs of real-life human faces without retro-targets. Stage (a) which involved with the used of a digital camera, can only be applied to the mannequin since this test object is rigid and does not having a movement effect like real-life human faces.

Standard digital caliper with the accuracy of 0.1mm was used to measure the linear distances between the selected natural features both on the mannequin and real-life human face with retro-targets. The caliper was calibrated where the value of zero was always started at the accurate scaling designed on the caliper. Each distance was measured three times and the average of the distances was calculated.

Data processing

As general, the data processing part consists of three stages, (a) photogrammetric bundle adjustment process for the determination of the 3D coordinates of simulated and real natural features, both on the mannequin and real-life human faces, respectively, (b) photogrammetric stereo orientation process which includes interior, relative and absolute orientation of stereo images and (c) photogrammetric stereo digitizing to digitize the selected craniofacial landmarks (using Vectorization module in DVP software).

In this study, the three sets of captured stereo images were processed separately. Each stereo image also involved with two different three-dimensional stereophotogrammetric mapping controls for absolute orientation; (a) by using signalized targets established on the photogrammetric control frame (known as control frame technique) and (b) by using the coordinates of the natural features on the craniofacial surface (known as natural features technique). For each process, the three-dimensional coordinates of the selected natural features were measured three times stereoscopically and the average of the coordinates was calculated. Figure 4 shows the process of measuring and digitizing craniofacial landmarks using DVP software.

Figure 4 Stereo digitizing using Digital Video Plotter (DVP) Photogrammetric Workstation.

RESULTS

The results consist of (a) the photogrammetric bundle adjustment 3D coordinate of the simulated natural features on the mannequin and natural features on the real-life human faces, (b) the 3D coordinates of simulated and real-life natural features from stereo digitizing via stereo images both from control frame technique and natural features technique, respectively. For data analysis, several simulated and real-life natural features on the mannequin and real-life human faces were selected as test points. Figure 5 and Table 1 shows the 3D coordinates of the test points on the mannequin, while Figure 6 and Table 2 shows the 3D coordinates of the test points on real-life human face

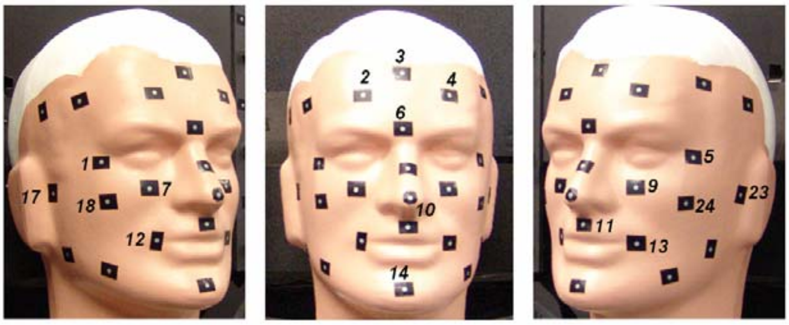

Figure 5 Selected test points (simulated natural features) on the mannequin

Figure 6 Selected test points (natural features) on the real-life human face

Table 1 3D coordinates of selected simulated natural features (test points) on the mannequin

ID	X (Bundle) (mm)	Y (Bundle) (mm)	Z (Bundle) (mm)	X (Natural Features) (mm)	Y (Natural Features) (mm)	Z (Natural Features) (mm)	X (Control Frame) (mm)	Y (Control Frame) (mm)	Z (Control Frame) (mm)
1	2511.989	970.216	79.364	2512.094	970.441	79.214	2508.227	970.135	83.696
2	2544.416	1017.719	101.152	2544.251	1017.747	103.030	2544.237	1019.448	92.477
3	2572.911	1033.141	98.123	2572.731	1033.129	99.636	2573.522	1035.283	89.164
4	2605.876	1016.298	100.410	2605.731	1016.444	100.140	2607.379	1018.057	90.253
5	2632.129	969.580	72.155	2632.939	969.557	73.763	2636.107	969.235	77.782
6	2570.732	992.318	111.301	2570.683	992.377	111.569	2571.523	993.595	100.341
7	2537.597	950.340	100.601	2537.463	950.465	103.157	2537.314	950.263	91.806
9	2603.435	949.249	101.844	2603.279	949.121	103.157	2604.948	949.123	92.187
10	2572.076	944.489	134.584	2572.158	944.353	130.836	2573.086	944.050	121.014
12	2540.603	913.976	102.880	2540.683	913.733	103.287	2538.629	912.959	105.816
13	2603.417	910.396	101.240	2604.033	910.282	102.656	2606.305	909.284	105.854
14	2568.218	881.307	122.330	2568.212	880.884	119.489	2568.891	878.834	108.282
18	2512.096	942.226	85.627	2512.272	942.251	85.166	2508.843	941.442	88.947
23	2646.820	942.718	27.912	2648.852	942.281	32.921	2652.165	942.159	35.919
24	2630.615	937.758	80.538	2631.061	937.660	81.476	2634.178	936.910	85.173

Table 2 3D coordinates of selected real-life natural features (test points) on the real-life human face

ID	X (Bundle) (mm)	Y (Bundle) (mm)	Z (Bundle) (mm)	X (Natural Features) (mm)	Y (Natural Features) (mm)	Z (Natural Features) (mm)	X (Control Frame) (mm)	Y (Control Frame) (mm)	Z (Control Frame) (mm)
1	2491.338	985.000	68.934	2491.755	985.135	68.794	2488.813	986.321	71.296
2	2523.993	1036.449	81.698	2524.068	1036.515	81.599	2520.641	1038.033	85.376
3	2569.566	1055.997	74.400	2569.694	1055.676	73.087	2569.869	1058.454	77.566
4	2610.507	1035.326	72.033	2609.074	1035.639	70.720	2610.867	1037.476	76.875
5	2636.100	981.551	58.166	2635.786	981.735	57.624	2641.375	981.870	63.259
6	2569.086	1009.795	98.967	2569.953	1010.796	94.976	2569.524	1012.802	99.670
7	2475.156	955.252	18.122	2472.732	954.173	22.391	2470.977	955.396	24.138
8	2526.461	962.162	100.254	2527.415	962.683	99.720	2524.307	963.469	102.862
10	2615.344	957.940	88.684	2615.75	957.788	87.994	2616.109	959.815	92.623
11	2645.743	953.631	2.235	2650.282	952.223	7.846	2653.849	953.441	12.415
12	2486.826	931.620	68.577	2487.030	931.462	68.650	2485.364	931.396	69.539
13	2572.501	956.154	128.982	2574.136	957.719	121.651	2573.149	958.973	125.210
14	2641.595	927.743	48.919	2642.165	927.169	49.094	2646.062	927.463	53.222
16	2520.099	911.163	99.649	2520.092	911.125	97.617	2519.689	912.138	99.452
17	2611.781	908.147	89.846	2612.145	907.762	89.663	2612.513	909.143	93.520

ANALYSIS

The preliminary analysis involved the linear distances between the set of the test points on the mannequin and real-life human face. In this analysis, the linear distances gained from bundle adjustment method was used as a *reference* to verify the accuracy of the natural features technique, control frame technique and caliper technique. Advanced analysis involved the study of the depth factor in the stereophotogrammetric measurements by control frame and natural point techniques. The linear distances analysis on the mannequin involved with 10 distances with 15 test points, while the test on real-life human face involved with 9 distances with 15 test points. The statistical analysis (mean, variance, standard deviation and root mean square error) of the differences between all the techniques with the bundle adjustment method was calculated. Table 3 and 4 show the results of the linear distances analysis both on the mannequin and real-life human face, respectively.

Table 3 Linear distances analysis between the test points on the mannequin

From point	To point	Caliper vs. bundle method (mm)	Natural features technique vs. bundle method (mm)	Control frame method vs. bundle method (mm)
2	4	-0.180	0.080	1.720
3	6	-0.350	-0.440	0.260
6	10	-0.210	-1.440	0.500
12	13	0.110	0.500	4.840
1	5	-0.110	0.610	7.660
17	7	-0.200	-0.370	-10.200
9	23	0.150	-2.000	-12.220
4	24	-0.110	0.120	0.900
2	18	-0.170	0.340	2.160
3	14	-0.320	-0.220	3.860
Statistics	*Mean*	-0.139	-0.282	-0.052
	Variance	0.023	0.641	35.909
	Std Dev	0.153	0.801	5.992
	RMSE	**0.207**	**0.849**	**5.992**

Table 4 Linear distances analysis between the test points on the real-life human face

From point	To point	Caliper vs. bundle method (mm)	Natural features technique vs. bundle method (mm)	Control frame method vs. bundle method (mm)
2	4	-0.110	-1.356	3.567
3	6	-0.029	-2.395	-1.606
6	13	-0.562	-2.012	-1.871
16	17	1.595	0.202	0.807
1	5	0.297	-0.698	7.636
7	8	0.664	-1.993	-1.656
10	11	0.627	-4.291	-2.867
4	14	-1.094	1.104	3.557
2	12	0.306	0.147	1.437
Statistics	*Mean*	0.188	-1.254	1.001
	Variance	0.530	2.401	10.494
	Std Dev	0.728	1.549	3.239
	RMSE	**0.752**	**1.994**	**3.391**

The study of the depth factor in the research were being the advance analysis method to prove that the use of natural features technique will enhanced the accuracy of anthropometric landmark measurements via stereo images. The *depth* is defined as the distances between the datum (average distances from camera lens to absolute photogrammetric control points) to the measured anthropometric landmarks along the z-axis. In aerial photogrammetric method, the depth value should not be more than 10% of the flying height in order to gain high accuracy measurements of an actual height of features. The similar formula can be successfully applied in close-range photogrammetry where the depth of all measured points in stereo model will gained higher accuracy in depth if the depth is about $\pm 10\%$ of the object distance. For example, for the object distance of 600mm, the maximum depth value is 60mm. In this research, which involved the comparison of control frame and natural features techniques in the measurement of anthropometric landmarks, the location of the landmarks from the datum is different (Figure 7).

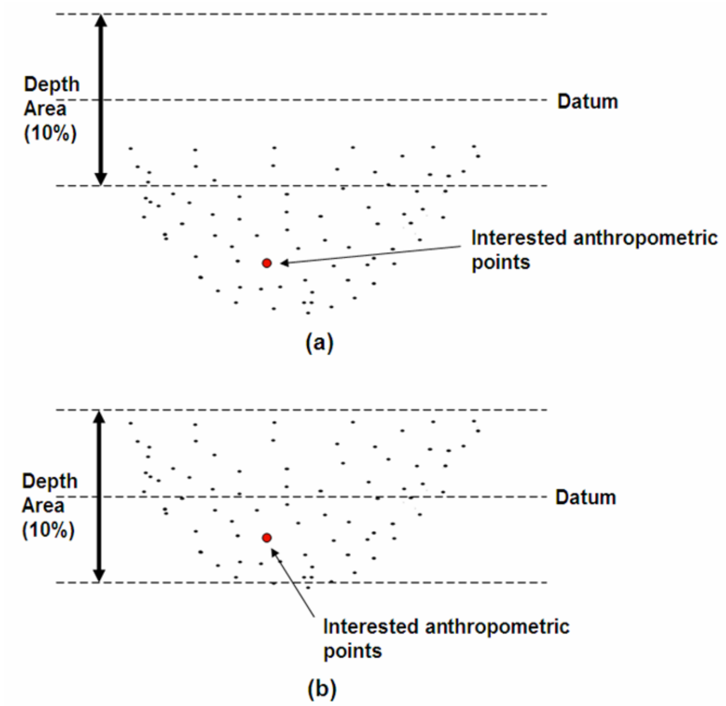

Figure 7 Location of craniofacial landmarks and the photogrammetric measurement datum of (a) control point technique and (b) natural features technique

The statistical analysis involved the two variable regressions between the errors in z coordinates versus the percentage of depth for each test points in both method and the plots of both results are provided (Figure 8 and Figure 9). As general, both plots show the logical results where the increase of depth value (percentage of depth) will increase the error in z coordinates of the anthropometric landmarks. The results also show that the natural features technique is more accurate than the control frame technique. The optimum accuracy for the configuration of the stereo cameras is 0.25mm and the depth percentages of 20% and below was recorded to be true with the accuracy of z coordinate within 0 to 1mm.

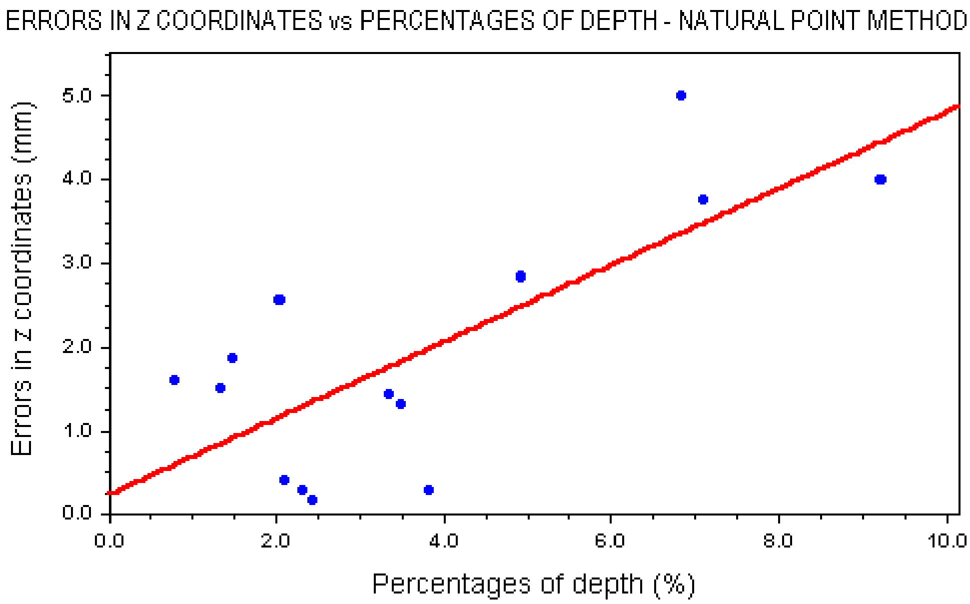

Figure 8 Depth analysis – natural features technique

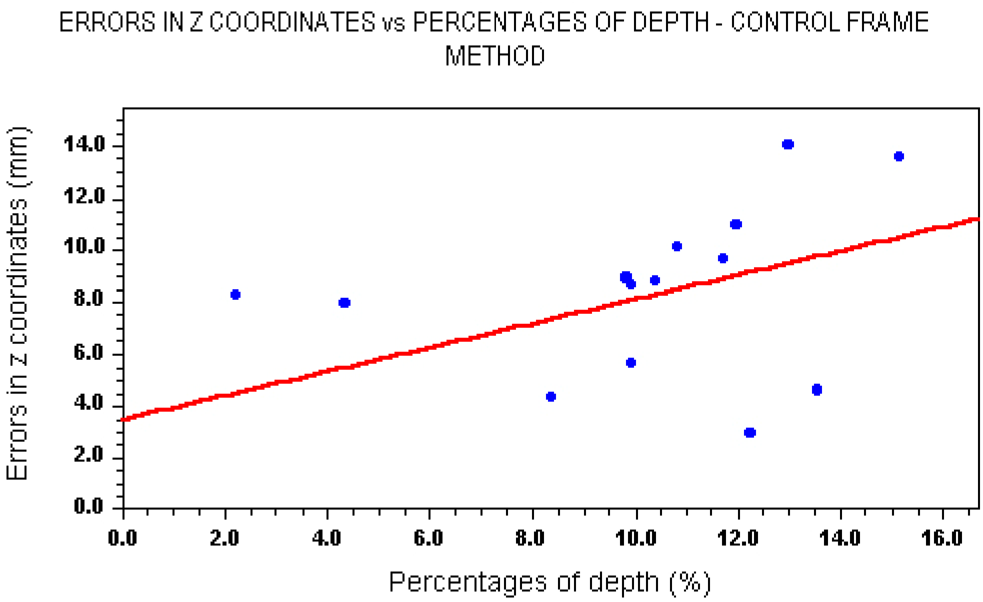

Figure 9 Depth analysis – control frame technique

The *F test statistic* was also used to verify the accuracy of the natural features technique. The test involved the analysis of population variance to test the significance of differences among the two techniques. The null hypothesis H_o (the accuracy of the two methods are the same) was tested against the alternative hypothesis H_A. The F-test for two population variances (variance ratio test) is suitable for testing the hypothesis since the accuracy of both methods is considered into account. The value is computed from the following formula:

$$F = \frac{S_1^2}{S_2^2} \qquad (1)$$

Where S_1^2 represent variance of the errors in z coordinates for control frame method and S_2^2 represent variance of the errors in z coordinates for natural point method. The results of the test are provided in Table 5.

The results show that with 12 degree of freedom, the calculated *F* value is 4.492958. The critical value for *F* (from *F*-Table) is 2.686637. With these results, we rejected the null hypothesis and it is statistically proved that the accuracy of the two techniques is not the same. It's also proving that the natural features technique was the accurate method for the measurements of the anthropometric landmarks on the real-life human facial surface.

Table 5 *F variance ratio test* results

Method	*Variance*	*Degree of freedom*	*F value (calculated)*	*Critical F value (Table)*
Control Frame	10.04033	12		
Natural Point	2.234681	12		
			4.492958	2.686637
		Decision	Reject Ho	

FINAL EVALUATION OF PROPOSED TECHNIQUE

For final evaluation of the natural features technique, the technique was tested on the real-life human face without having any signalized targets to represent the natural features. The number of six selected natural features was used as test points and accurately measured by photogrammetric bundle adjustment (Figure 10). The 3D coordinates gained from the bundle adjustment method were selected as reference values. At the same time the similar selected natural features was measured using natural features and control frame techniques (Table 6). The 3D coordinates of both techniques (acquired from stereo measurements) were than compared with the 3D coordinates gained from bundle adjustment. The root mean square error (RMSE) value of the 3D coordinate differences was than calculated (Table 7).

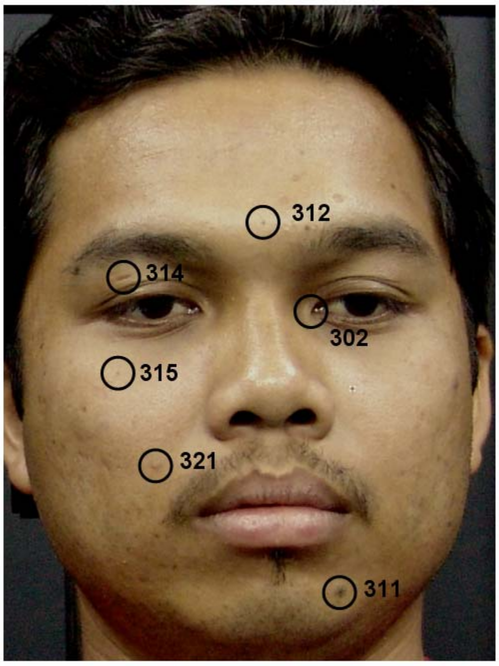

Figure 10 Selected natural features as test points

Table 6 3D coordinates of the selected natural features as test points

ID	X (Bundle) (mm)	Y (Bundle) (mm)	Z (Bundle) (mm)	X (Natural Features) (mm)	Y (Natural Features) (mm)	Z (Natural Features) (mm)	X (Control Frame) (mm)	Y (Control Frame) (mm)	Z (Control Frame) (mm)
302	494.987	441.666	135.194	494.915	441.630	135.041	496.668	441.330	123.338
311	503.696	350.880	142.704	503.782	350.316	143.927	505.572	347.963	130.074
312	477.479	469.187	150.929	478.318	469.434	149.722	478.954	469.753	136.810
314	432.230	452.385	138.444	432.199	452.540	138.132	431.738	452.267	124.461
315	431.687	421.251	139.741	431.735	421.890	140.836	431.837	421.257	124.461
321	442.932	391.326	145.140	442.787	391.572	145.086	443.514	389.738	131.196

Table 7 Results of the test

ID	X (Natural Features-Bundle) (mm)	Y (Natural Features-Bundle) (mm)	Z (Natural Features-Bundle) (mm)	X (Control Frame-Bundle) (mm)	Y (Control Frame-Bundle) (mm)	Z (Control Frame-Bundle) (mm)
302	-0.072	-0.036	-0.153	1.680	-0.336	-11.856
311	0.085	-0.564	1.222	1.875	-2.917	-12.630
312	0.838	0.246	-1.207	1.474	0.565	-14.119
314	-0.031	0.154	-0.312	-0.492	-0.118	-13.983
315	0.047	0.638	1.094	0.149	0.005	-15.280
321	-0.145	0.245	-0.054	0.581	-1.588	-13.944
Mean	0.120	0.113	0.098	0.878	-0.731	-13.635
Std Dev	0.330	0.363	0.838	0.865	1.173	1.105
Variance	0.108	0.132	0.702	0.748	1.377	1.222
RMSE	**0.351**	**0.381**	**0.843**	**1.232**	**1.383**	**13.680**

CONCLUSION

In the paper, the use of stereophotogrammetric method has been discussed for measurements of craniofacial landmarks. The use of natural features technique was statistically approved and found to be an effective method to improve the accuracy of the non-contact craniofacial anthropometric measurements (*mannequin test* - RMSE value of 0.8mm and 6.0mm both for natural features technique and control frame technique, respectively, *real-life human face* – RMSE value of 2.0mm and 3.0mm for natural features technique and control frame technique, respectively). In-term of the accuracy of the 3D coordinates of the craniofacial landmarks (especially for Z coordinate), the RMSE value of 0.8mm was gained by using the natural features technique compared to the control frame technique with the RMSE value of 14.0mm.

By using the natural features technique, there is no need to shorter the camera to object distance and the optimum coverage of the stereo mapping were maintained. The shape and location of the natural points was easily obtained since the setup of the camera system covered the craniofacial measurement area. For high accuracy absolute orientation of the stereo models, the selected natural features need to be well distributed in the overlapping area. The number of six natural features was needed for optimum accuracy of absolute orientation.

In the research, the proposed method need medium extra time to proceed since the additional time was needed to obtain the 3D coordinates of the selected natural features. The Australis camera calibration was used to run the bundle adjustment process for high accuracy 3D coordinates of the natural features. Since the similar software was used for calibrating the stereo cameras and measuring the 3D coordinates of the natural features, there is no additional cost for obtaining the natural features 3D coordinates using other third party software.

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PHOTOGRAMMETRY AND 3D LASER SCANNING AS SPATIAL DATA CAPTURE TECHNIQUES FOR A NATIONAL CRANIOFACIAL DATABASE

ZULKEPLI MAJID (zulkepli@fksg.utm.my)
Universiti Teknologi Malaysia

ALBERT K. CHONG (chonga@albers.otago.ac.nz)
University of Otago, New Zealand

ANUAR AHMAD (anuar@fksg.utm.my)

HALIM SETAN (halim@fksg.utm.my)
Universiti Teknologi Malaysia

ABDUL RANI SAMSUDIN (dental@kb.usm.my)
Universiti Sains Malaysia

Abstract

Photogrammetry is a non-contact, high-accuracy, practical and cost-effective technique for a large number of medical applications. Lately, three-dimensional (3D) laser scanning and digital imaging technology have raised the importance of digital photogrammetry technology to a new height in craniofacial mapping. Under the support of the Eighth Malaysian Development Plan, the Ministry of Science, Technology and the Environment (MOSTE) Malaysia allocated a grant to establish procedures for the development of a national craniofacial spatial database to assist the medical profession to provide better health services to the public. To populate the database with normal and abnormal (malformation, diseased and trauma and burn victims) craniofacial information, it is necessary to evaluate the technology needed to capture the essential data of craniofacial features.

The paper provides a discussion on the basic features of the spatial data and the data capture techniques. Both are needed for the establishment of a national spatial craniofacial database. The discussion includes a brief review of the current status of two selected high-accuracy craniofacial spatial data capture techniques, namely, digital photogrammetry and 3D laser scanning. The paper highlights a system which has been developed for a Malaysian craniofacial mapping project.

Laboratory tests with mannequins showed that the photogrammetric and 3D laser scanning system could achieve an accuracy exceeding the design specification of ±0·7 mm (one standard deviation) for all the measured craniofacial distances. However, tests with two living subjects showed that the accuracy was in the order of ±1·2 mm because of facial movement during data capture.

KEYWORDS: 3D laser scanning, close range digital photogrammetry, craniofacial information system, forensic investigation, pre-intervention data for plastic surgery, spatial database

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Introduction

In 2001, the Ministry of Science, Technology and the Environment (MOSTE) approved a multi-million dollar grant for research to develop a craniofacial spatial database in Malaysia. Three main research groups are involved in the research. They are the Universiti Teknologi Malaysia (UTM), the Universiti Sains Malaysia (USM) and SIRIM Berhad, which is an appointed government company. In addition, the University of Otago is involved as a data capture consultant. Similar developed databases are limited to a few countries (Farkas, 1994; Kolar and Salter, 1997, p. 11; Ferrario et al., 1999). Essentially, the national database must be able to handle many forms of spatial data in raster format such as charge-coupled device (CCD) camera images, computerised tomography (CT) scanner images and scanned cephalometric radiographs. In addition, many forms of spatial vector data are essential, which may include data obtained from photogrammetric systems, three-dimensional (3D) laser scanning systems or conventional anthropometric measurement techniques. Attribute data are also needed in the database. Examples are patient medical details and pre- and post-surgical intervention data.

For the pre-intervention planning of craniofacial corrective and reconstruction surgery, several forms of 3D spatial data must be available. This craniofacial feature and shape information includes digital 3D craniofacial surface data, 3D soft tissue data, 3D anthropometric measurement, 3D CT scan data, 3D hard tissue data and, occasionally, digital 2D cephalometric radiographs. Also, secondary spatial data such as a patient's parents' or siblings' craniofacial features may be required for planning purposes. These data-sets are essential for planning of a particular type of craniofacial surgery in which accurate pre-surgical data is not available. For example, an accident or burn patient may not have accurate pre-intervention data for reconstructive surgery. Monitoring of post-surgical intervention also requires accurate pre-surgery craniofacial spatial data.

Spatial craniofacial data of the "normal range" group (Farkas, 1994, p. 73) of the population is needed to plan craniofacial reconstruction of malformation patients because the normal data are often used to provide the correct dimensions for surgery (Cutting et al., 1998; Madjarova et al., 1999). Kolar and Salter (1997, p. 232) stated that the absence of adequate comparative data for non-European populations is increasingly becoming a problem for analysing patterns of dysmorphology or for planning surgical corrections. In addition, the normal data is required for forensic applications, namely: (1) identifying a body (skeletal remains), (2) predicting the current profile of the individual and (3) estimating the age of the individual (Giles and Elliot, 1963).

Malaysia is a multiracial country where non-Europeans (Malay, Chinese and Indian) form the bulk of the population. However, the cost of setting up a national database is expensive, in particular for the craniofacial data capture. Therefore, it is essential that proper planning and investigation be carried out before commencing the data capture phase. This research provides an evaluation of current craniofacial spatial data capture techniques and systems. On the basis of the evaluation a combined process was developed employing both photogrammetric and 3D laser scanning technologies.

The paper provides a discussion of the basic features of the spatial data and the data capture techniques. Both are needed for the establishment of a national craniofacial spatial database. The discussion includes a brief review of the current status of two selected high-accuracy craniofacial spatial data capture techniques, namely, digital photogrammetry and 3D laser scanning. The paper also highlights a system which was developed for a Malaysian craniofacial mapping project.

THE MALAYSIAN CRANIOFACIAL SPATIAL DATABASE

This database was initiated to provide a comprehensive set of craniofacial spatial data of all the racial groups for both corrective and reconstructive surgery. Malaysia has a large number of ethnic groups and tribal subgroups. To populate the database with the craniofacial data of all racial groups would require massive resources. Consequently, the ethnic Malay group was selected for the initial stage of the research. In the subsequent stages, more ethnic groups could be included in the database.

The initial research grant provided the opportunity to develop a photogrammetric/3D laser scanning spatial data capture system. Such a system should be portable, should provide high-accuracy anthropometric linear and angular measurements, should provide high-accuracy 3D surface (skin) models of the craniofacial structure and should provide high-resolution stereo photographs for 3D surface rendering. The grant also provided for the opportunity to set up a comprehensive spatial database, which could be used for corrective and reconstructive surgeries, forensic investigation, safety headgear manufacturing and scientific research. Technically, for a complete representation of the ethnic Malay population, the spatial data should come from males and females of all ages. A total of 3600 individuals were needed for this stage of the project. Details of the spatial data requirement and accuracy aspects are discussed in this section. Next, the reasons for considering the ethnic groups, the inclusion of males and females and of age grouping are addressed.

Spatial Data Requirement

According to Farkas (1994), a basic craniofacial spatial database should contain a set of anthropometric linear and angular measurements, which could be used to define the shape and size of human craniofacial features. Linear measurements could be projective or tangential (Fig. 1). Examples were the width of the forehead and the circumference of the head, respectively. The angular measurements could be inclination or angles. Examples were the

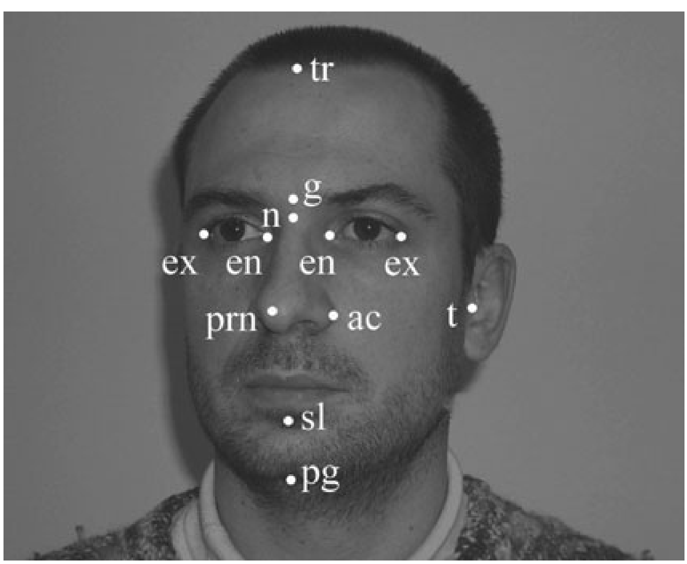

FIG. 1. Standard anthropometric landmarks.

inclination of the anterior surface of the forehead and the mentocervical angle, which was formed by the upper contour of the chin and the surface beneath the mandible, respectively. A complete craniofacial examination required 135 linear and 59 angular measurements (Farkas, 1994). Nevertheless, the basic set of anthropometric measurements was no longer adequate for the modern multi-purpose national database, which would be required for quality corrective and reconstructive surgeries, forensic investigation and scientific research.

After consultation with a group of craniofacial surgeons from USM it was clear that the database should provide data for the following modern applications: (1) evaluating the abnormality of a patient's craniofacial features (for example, asymmetry of the head, face and jaws); (2) pre-surgical intervention planning and post-surgical evaluation of malformed craniofacial features; (3) pre-surgical and post-surgical evaluation of trauma patients; (4) forensic identification of both the living (missing person) and the dead (skeletal remains) and (5) digital 3D models for solid modelling. To satisfy the requirement of the first application, stereoscopic photographs were needed to capture the anthropometric linear and angular measurements. In addition, the stereo photographs should be available for updating and referencing in the future. The data requirements of the second, third and fourth applications were similar. To carry out these applications, 3D models of soft tissue (skin surface) and hard tissue (skull, jaw and teeth) were needed. Photogrammetry, 3D laser scanning technique, structured light modelling and many other developed techniques could obtain the soft tissue model. CT scan and cephalometric radiograph and magnetic resonance (MR) image could provide the hard tissue model. In the fifth application, a 3D solid model of the skin surface and the hard tissue would be needed for patient consultation and classroom illustration purposes. These solid models could be created using rapid prototyping technology (RPT).

Spatial Data Accuracy

This was one of the most important factors in the development of the photogrammetric/3D laser scanning system because it could affect the accuracy of the spatial database. To review the accuracy of the existing databases one needs to go no further than the set of data provided by Kolar and Salter (1997). In the data, a set of manually obtained anthropometric linear and angular measurements was available. The authors provided the population standard deviation of all the important anthropometric measurements of a group of 18-year-old females. The smallest recorded standard deviation of these anthropometric measurements was 0·7 mm. That is, the population showed a deviation of 0·7 mm for the distance connecting two particular anthropometric marks. In other words, a 0·7 mm difference or one standard deviation of the population means in the anthropometric distance between two individuals was not noticeable visually (Farkas, 1994, p. 73; Evereklioglu et al., 2002). However, Kolar and Salter (1997) also argued that a 1 mm inferior dislocation of both endocanthion (en) and exocanthion (ex) (see markers in Fig. 1) could produce an obvious deformity even though the measurements of the eye fissures, length, width and inclination were otherwise symmetrical. Thus, the accuracy in locating some craniofacial landmarks was more important than others.

Gäbel and Kakoschke (1996) reported a clinical requirement of all facial measurements to have an accuracy of 0·1 mm. However, the authors did not refer to any specific standards or specifications. Similarly, Ayoub et al. (1998) stated that a relative accuracy of 0·5 mm is required for work relating to 3D spatial data capture for surgical planning purposes. Again, the specific standards or specifications were not stated. It was difficult to identify the majority of the anthropometric marks for subsequent measurement to such high precision except where a signalised target was placed over the position permanently. Obviously two types of accuracy can be identified: (1) digitising accuracy, which depends on the system and the signalised target used, and (2) landmark location accuracy, which depends on the anthropologist or the clinician who place the signalised target. On the whole, any substantial improvement in the accuracy also increases the cost of capturing the data. Moreover, the skill of personnel required to capture the data from images can also increase substantially. The demand for skilled personnel in rural hospitals may put a strain on the budget of setting up a national database.

After consultation with a group of craniofacial surgeons it was clear that the existing accuracy of the manually obtained anthropometric measurement was adequate. Consequently, for the first application, a value of 0·7 mm was adopted (Kolar and Salter, 1997) for the overall anthropometric linear measurement accuracy. That is, the stereoscopic photographs should provide an accuracy of ±0·7 mm at one standard deviation for all the measured vectors. For the second and third applications an accuracy of ±2·0 mm was agreed. This value was determined by the contour tracing method, which is significantly less accurate than the spot elevation method (Wolf and Dewitt, 2000). In conjunction with photogrammetry, a laser-based structured light triangulation technique (3D laser scanning) was used to obtain 3D surface data, recognising the disadvantage of possible patient movement between the stereo photography and the scanning. In view of the 3000 to 4000 patients required for the first phase of the project, the efficiency of such technology as 3D laser scanning outweighed the drawback.

METHOD OF CRANIOFACIAL SPATIAL DATA CAPTURE

In view of the accuracy requirement of the spatial data and the amount of data needed to populate the database, it was essential to review the techniques for spatial data capture, particularly, an efficient 3D surface remote measuring technique. D'Apuzzo (2003) and Hu and Stockman (1989) provide discussion on the various remote measuring techniques. The former provides a schematic comparison of three popular techniques based on the accuracy, hardware cost, acquisition time, and processing time and ease of use. The latter gives a list of four basic common remote measuring techniques, which are as follows:

(1) Stereo disparity: the method simulates the two eyes of a human. Depth can be measured in manual or automated mode. This technique is commonly known as photogrammetry.
(2) Structured light: an artificial light source such as a laser is used to illuminate a surface with a pattern. A photograph of the patterned surface is used to compute the depth using the triangulation algorithms. A common precise method in this category is known as 3D laser scanning in medical literature.
(3) Direct ranging or profiling: an example is a laser rangefinder, which measures depth by using the time of travel of the laser beam.
(4) "Shape-from" techniques: these monocular approaches recover the relative depth from texture, from shading, from contours or from motion; resulting in the surface orientations with respect to a viewer-centred coordinate system.

Many commercial systems have been developed based on these or variants of these techniques. However, it was decided to develop a system based on the technology the research team was familiar with and which would be adequate for the project. Some of the selection factors were based on the information provided in D'Apuzzo (2003). Consequently, only photogrammetry and 3D laser scanning were selected for the project. A brief discussion of the selected techniques and the conventional anthropometric measurement technique are provided below.

Conventional Measurement Technique

No amount of argument in favour of the introduced new method could be considered complete without a proper discussion of the existing technique. Traditionally, craniofacial data was obtained using standard anthropometric instruments such as callipers, measuring tapes, compasses, protractors and angle finders (Kolar and Salter, 1997). Farkas (1994) stated that the anthropometric examiner should be familiar with (a) the areas in which the tip of the instrument used must be pressed to the bony surface to obtain correct measurement and (b) the areas where the instrument barely touches the skin surface at measurement. Farkas (1994) argued that accurate measurement required correct use of the standard anthropometric instruments and knowledge of the peculiarities of the landmarks. Standard tools for curve surface measurement could produce large errors because the line and angle of measurement were subjected to the interpretation of the anthropometric examiner. In addition, both the examiner and the patient were often faced with uncomfortable and lengthy measurement sessions. The conclusion was that only a small number of measurements would still require a standard anthropometric instrument. These measurements would include all the cranial landmarks above the hairline, the circumference of the head and regions not captured by photogrammetry. The missing regions in photogrammetry and 3D laser scanning technique were mainly the result of occlusions and obstruction by hair.

Stereo Disparity: Photogrammetry

Single-, stereo- or multiple-image close range photogrammetry has been used for the recording and mapping of human body parts since the early 1900s (Mitchell and Leemann, 1996). Generally, medical and dental professionals favoured the simple single image measurement techniques. They used the images to determine the length of the feature, the angle between features or relative depth of features (Akimoto et al., 1993; Brusati et al., 1996; Berger et al., 1999; Fanibunda and Thomas, 1999; Nechala et al., 1999). Nevertheless, 3D model generation, contour plots of the craniofacial and 3D anthropometric measurements have been researched extensively (Domokos and Kismartoni, 1974; Newton, 1974; Wright et al., 1974; Deacon et al., 1991; Banda et al., 1992; Ferrario et al., 1995, 1996; D'Apuzzo, 1998, 2002, 2003; Ferrario et al., 1999; Frey et al., 1999).

Images for close range photogrammetry can be acquired using film-based cameras, analogue video cameras or digital still-frame cameras/video cameras. Films must be scanned into digital form using scanners; analogue video must be frame-grabbed into digital form while digital systems output images in digital form directly (Schenk, 1999). By and large, a digital system is the most advantageous because film scanning requires additional resources.

Camera calibration is essential for all photogrammetric cameras which are involved in accurate measurements. Camera calibration software has become more user-friendly for non-metric film-based cameras and digital cameras in recent years (Dowman and Scott, 1980; Fryer, 1989; Beyer, 1992; Peterson et al., 1993; Fraser and Edmundson, 1996; Shortis et al., 1996). The process includes the determination of the CCD format size, principal point of autocollimation, the principal distance, and the radial lens distortion parameters.

Once a stereopair of photographs of the craniofacial area was taken, interior, relative and absolute orientation could be carried out either manually or automatically using soft-copy photogrammetric software (Schenk, 1999). Also, points of interest on the stereomodel could be captured manually or automatically (Schenk, 1999; Wolf and Dewitt, 2000). In the latter, a digital surface model (DSM) of the stereomodel could be obtained instantly. However, there is a small amount of editing required because the craniofacial structure has a complex shape.

Editing could involve the removal of error and the addition of breaklines and ridge lines (Schenk, 1999). Nonetheless, the 3D point cloud created through stereo photogrammetry consists of a set of points with each point having a set of 3D coordinates. The spatial accuracy of the technique depends mainly on the geometry of the images used, the resolution of the CCD camera and the image processing technique. Generally, the desired mapping accuracy can be controlled simply by altering the focal length of the lens, the object distance and the pixel resolution of the CCD of the camera. Relative object space accuracy of 0·5 mm or higher can be achieved using stereo or multiple photographs routinely (Newton, 1974; Burke et al., 1983; Hay et al., 1985; Deacon et al., 1991).

Structured Light: Triangulation

This technique is often known as 3D laser scanning in the medical journals and the same name is used in this paper. The surface of the object is illuminated with an artificial light, which may be any structured light or any shade of pattern. Assuming that the light is projected in a single plane, a triangulation algorithm can determine the depth of the surface (Fig. 2). Details of the mathematics can be obtained in Boyer and Kak (1987), Sanderson et al. (1988) and Hu and Stockman (1989). Generally, the system consists of a structured laser light source, a light projection system and a digital imaging system. The structured laser beam projects an ultra-thin profile on the object, which is photographed by a CCD camera mounted close to the projector. The relative position (a vector) between the internal reference point of the projection system and the camera lens is fixed. In addition, the angle of each projected laser profile plane and the angle of the camera optical axis are calibrated in advance. Subsequently, the *x*, *y* and *z* coordinates of the object space position of each pixel on the object can be computed using the scale of the photography, the relative positional vector and the known angles. A least squares technique is used to compute a set of optimum 3D coordinates of the object surface. The texture and radiometric value of the CCD images may be added to the 3D data to obtain a realistic surface model of the object. Additional information on the system for medical application can be found in Bush and Antonyshyn

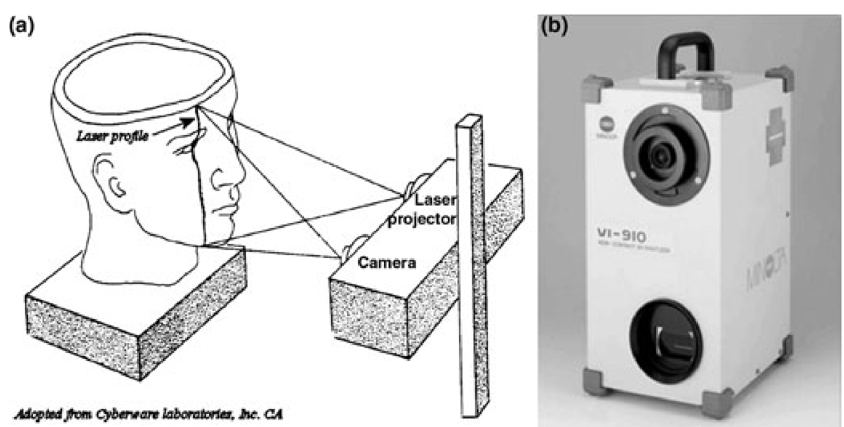

FIG. 2. (a) Structured light triangulation technique. A laser beam is projected onto the surface and the adjacent camera records the position of the beam. During a scan many hundreds of profiles are recorded along the surface. (b) A Minolta VI-910 laser scanner.

(1996), Cacou et al. (1997), Yamada et al. (1998), O'Grady and Antonyshyn (1999) and Bernardini et al. (2001). The spatial accuracy of a triangulation system is dependent on the focal length of the camera, the object distance, pixel size of the CCD camera, the number of cameras used and the mathematics, which determines the centre of the projected light beam. Kuroda et al. (1996) reported a measurement error of 0·05 mm using dual high-precision 3D-VMS250R CCD cameras produced by UNISN, Inc., Osaka, Japan; Bush and Antonyshyn (1996) gave a spatial resolution of 0·5 to 2 mm in x, 0·6 mm in y and 0·1 to 0·4 mm in z (depth) for a single-camera Cyberware 3030RBG digitiser. Minolta gives a depth precision ranging from 0·04 to 0·09 mm for the VI-910 system.

Generally, an off-the-shelf system is fully supported by a suite of software, which includes system calibration, data capture and data editing. To start a scanning session it is necessary to calibrate the system with a supplied calibration chart, which is placed on a rotary stage controller in front of the camera. A view of the scan area is displayed on the system viewfinder. The data capture phase is fully automated. The speed of point capture may range from 15 000 to 230 000 points per second. After a scan the 3D point cloud may be displayed and edited on the computer screen using third-party software such as RapidForm (INUS Technology Inc., Seoul, Korea).

Advantages and Disadvantages

The major advantages of photogrammetry are: it is non-invasive and instantaneous, it offers high accuracy and real-world colour and texture and it provides a permanent record. A permanent record allows re-measurement if it is needed. The major disadvantages are: there is lack of soft (skin and flesh) and hard (bone) tissue registration and there are always occlusions or obstructions on the images. The major advantage of 3D laser scanning is its speed of point capture and its ultra-high accuracy. There are three drawbacks for the present application which are (1) accuracy can degrade substantially if the patient moves during the process of scanning or in between scans, (2) a dark skin colour can affect the intensity of reflected light, (3) creating breaklines for ridges and valleys is both tedious and slow and (4) there is no permanent record as with the photogrammetry technique.

Based on the advantages and disadvantages of the discussion above laboratory tests were carried out. The techniques complement each other. One works at high speed and the other provides a permanent record of high-quality images.

General Considerations for the Spatial Data Capture

Non-contact Anthropometric Measurement

The standard anthropometric technique requires physical contact by the anthropometric examiner throughout the measurement session. Physical contact is not always desirable where religious or personal constraints forbid such contact. Conventional anthropometric measurement tools such as a sliding calliper can be very sharp. These tools can cause injury if a child becomes uncooperative during a measurement session. In addition, many areas on the face are very sensitive to touch, which may cause error in the measurement (Newton, 1974). Furthermore, Wright et al. (1974) argued that restraining an uncooperative patient often resulted in grimacing or distortion of the patient's facial features. In view of the fact that photogrammetry and 3D laser scanning are non-contact technologies, approved by the project advisory panel, both techniques are considered vital for the data capture exercise.

Manual or Automated Technique for Anthropometric Measurement

Various authors have discussed advantages and drawbacks of automated anthropometric measurements. Automated anthropometric measurement involves pre-targeting anthropometric mark positions with signalised targets. These targets can be recognised by computer software (Grüen and Baltsavias, 1989; Bush and Antonyshyn, 1996; Ferrario et al., 1996; Cacou et al., 1997; D'Apuzzo, 2002). Ferrario et al. (1996) reported an accuracy of 0·1 mm for all three coordinates of 16 standardised facial landmarks automatically collected using a stereo camera system. Recently, Hattori et al. (2002) reported success with pre-coding targets for automated recognition in industrial vision metrology. Pre-coding targets may be used to identify and digitise the landmark automatically (see Fig. 1 for sample of landmark identification). At this stage there is no plan to implement this technique in the project.

To satisfy the spatial data requirement, which is discussed elsewhere in the paper, each phase of the data capture needs to be examined. Firstly, anthropometric linear and angular data are needed; secondly, a high-quality stereo-image is needed for future updating, referencing and 3D surface rendering; and thirdly, an accurate 3D surface model of the craniofacial area is needed. To obtain anthropometric angular data requires human observation of a photogrammetric stereomodel. The complexity of the arc and angle can only be appreciated by studying the specification given in Farkas (1994) and Kolar and Salter (1997). Consequently, an automated anthropometric landmark measurement technique satisfies the requirement only partially (about 70% of the measurements). However, one major benefit is that pre-signalised targets can be used to provide control points, which can help tie adjacent stereomodels together. In addition, these targets can be used to tie the laser 3D scan coordinates to the photogrammetric coordinate reference system. Consequently, the Ferrario et al. (1996) automation technique is applied for 16 standardised anthropometric landmarks, which are used as control points. The method of applying pre-signalised targets is explained in the next section.

Design of Pre-signalised Targets

For the stereo photogrammetry technique, Ferrario et al. (1999) applied 2 mm reflective markers and Cacou et al. (1997) applied 5 mm diameter blue vellum paper spots on the landmarks. Ferrario et al. (1999) reported an accuracy of 0·1 mm using an automated digitising technique while an accuracy of 0·5 mm using a manual digitising technique was reported by Newton (1974). For the 3D laser scanning technique, Bush and Antonyshyn (1996) used 2 mm diameter fluorescent markers. The authors reported an accuracy of 0·6 mm for signalised landmarks and an accuracy of 1 mm for non-signalised landmarks of a 3D laser scanned model. The present research showed that the use of pre-signalised targets in the stereo photographs gave measurements of equally high accuracy. Also, tests showed that these targets provide high-accuracy connection between adjacent stereomodels. Subsequently, they provided high accuracy for the transformation of the 3D laser scan coordinates to the photogrammetric coordinate reference system. However, it is clear that the placing of the targets required an experienced anthropometric examiner.

Photogrammetric Control

Photogrammetric control for stereo photography of the craniofacial mapping is well documented. In Savara and George (1984) a typical frame was placed over the patient's head;

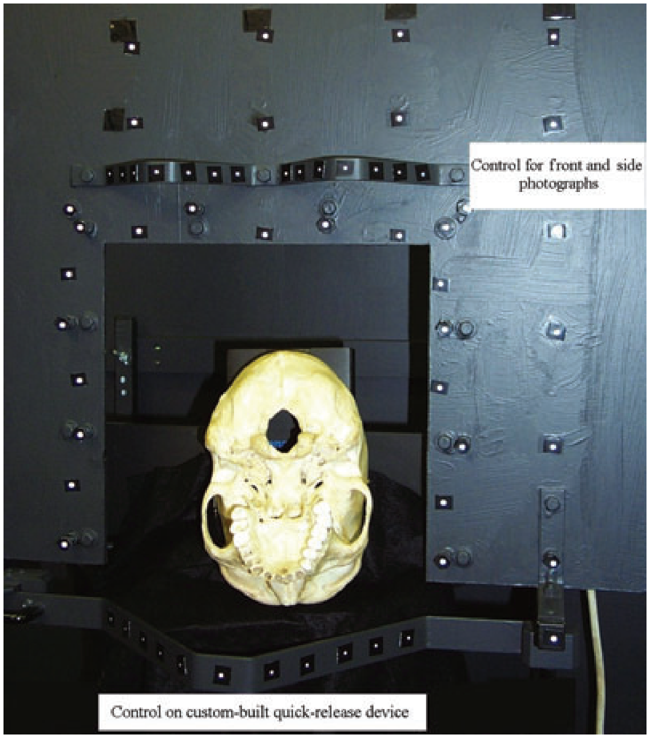

FIG. 3. Control frame for the photogrammetric technique. The positions of the targets provide an optimum control configuration for the side stereo photographs.
This figure appears in colour in the electronic version of the article and in the plate section at the front of the printed journal.

in Peterson et al. (1993) a frame was placed near both sides of the head and in Schewe and Ifert (2000) control targets were placed on a helmet. These three designs almost certainly covered all published photogrammetric control configurations. Frequently, these controls were attached to a cephalostat for study involving the lower craniofacial area. Fig. 3 shows the photogrammetric control configuration, which was based on the designs of Savara and George (1984) and Peterson et al. (1993).

Matching of Photogrammetric Measurement and Laser 3D Scanned Model

Surface registration was undertaken to determine the transformation parameters between the laser 3D scan and the photogrammetrically derived surfaces (McIntosh and Krupnik, 2002). Theoretically, the two data-sets should refer to the same coordinate system. However, instrumental error and patient movement could introduce a misalignment between the surfaces. McIntosh and Krupnik (2002) argued that a seven-parameter conformal transformation could be manually performed using pre-marked anthropometric landmarks. The process reduces the errors significantly. Consequently, the present research established a set of signalised anthropometric landmarks to provide accurate surface registration. These landmarks, which are depicted in Fig. 1, are *tr*, *n*, *prn*, *pg*, *sl* and *ex*.

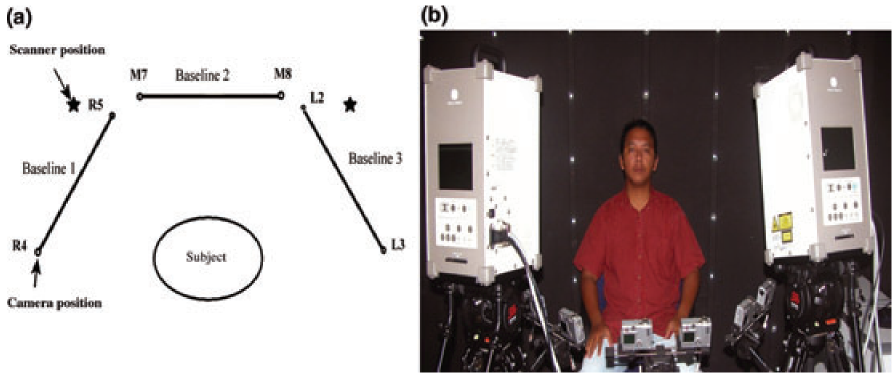

FIG. 4. (a) The craniofacial mapping camera and laser scanner configuration. (b) The Canon PowerShot S400 digital cameras and the laser scanner. Note that the cameras were wired to a single firing device and the prototype console was disconnected for copyright reasons.
This figure appears in colour in the electronic version of the article and in the plate section at the front of the printed journal.

THE MALAYSIAN CRANIOFACIAL DATA ACQUISITION SYSTEM

System Set-up

A review of existing surgical planning requirements showed that the Malaysian system should be capable of capturing high-quality digital stereo-images covering the whole craniofacial area instantaneously. The instantaneous imaging of the whole area avoided errors which could be introduced as a result of facial movement in between imaging of the remaining craniofacial area. The mapping covers the area from left ear to right ear (including all the anthropometric marks of the ears) and from hairline (*tr*) to the lowest point in the midline on the lower border of the chin (*gn*). To photograph the mapping area simultaneously, three sets of digital stereo cameras were used, which consisted of six Canon PowerShot S400 (4·0 megapixel) digital professional cameras. A synchronised power and shutter switch fired the six cameras simultaneously. In addition, the same craniofacial area was to be scanned by the 3D laser scanning method simultaneously. After the initial evaluation of a few products, the Minolta VI-910 3D digitiser was selected and two of these scanners were used to scan the whole craniofacial area (Fig. 4). A minimum of four well-distributed photogrammetric control points was allocated to each stereopair of images. Signalised targets were used for all standardised anthropometric landmarks. The targets were also used for the registration of the photogrammetrically derived coordinates with the coordinates obtained using the 3D laser scanning technique.

Calibrating the Cameras

To provide regular camera lens calibration for the six digital stereo cameras or when a new camera is added, a simple portable device was built for the purpose (Fig. 5). The calibration range required to be photographed with a high-precision Invar bar in the middle of it. The range can be rotated to allow four or more convergent photographs to be taken for a self-calibration. In the bundle adjustment, the lens parameters can be determined accurately (Beyer, 1992; Atkinson, 1996; Fraser, 2000). The process is simple because it is not essential to calibrate the range beforehand.

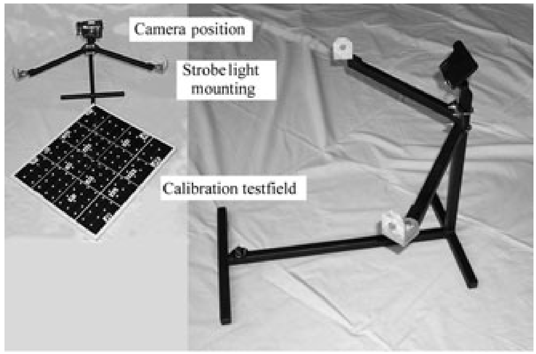

FIG. 5. A purpose-built camera calibration system.

Evaluating the Camera Synchronisation Device

To determine the suitability of low-cost digital cameras for high-accuracy anthropometric landmark measurement, it was necessary to study the reliability of the synchronisation technique. The cameras were connected to an electronic shutter activator which was developed by Graphic Media Research, Cannon Falls, Minnesota, USA. A shallow press of a button prepared the cameras for the synchronisation. Subsequently, a deep press activated the shutters simultaneously. To determine whether the three stereopairs of photographs were taken simultaneously, a simple test was carried out. A plumb bob was hung from the ceiling above the patient's chair. The plumb bob would be allowed to swing about 100 mm from the face of the photogrammetric control frame (Fig. 6). A white marker was placed on the plumb string just above the plumb bob. The plumb bob would be released at a specified elevation and allowed to go through a few full swings. Subsequently, the cameras' shutters were released when the plumb bob moved close to the lowest point of the swing while viewing from camera M8 (Fig. 4). The entire test procedure was repeated nine times. The cameras were turned off between each set of tests. Both Australis and DVP software were used to compute the position of the white marker for each set of stereopairs. In total 45 stereopairs of images were relatively oriented and the position of the white markers was subsequently computed from each stereopair.

Calibrating the Photogrammetric Control Frame

The photogrammetric control frame (Fig. 3) requires similar calibration. To calibrate the control frame four or more convergent photographs are taken with a high-precision Invar scale bar placed in the middle of the control frame. Again, a bundle adjustment is needed to determine the coordinates of the signalised targets. It is not necessary to have any previous known control point in the adjustment as in the case of an absolute orientation of a stereomodel.

Assessment of the Quality and Reliability

To monitor the quality and reliability of the measurement obtained by the photogrammetric/3D laser scanning system, the system needed to be tested using a rigidly constructed mannequin. Initially, signalised targets are placed on the anthropometric landmarks of the mannequin. The coordinates of the signalised targets are determined by a set of convergent

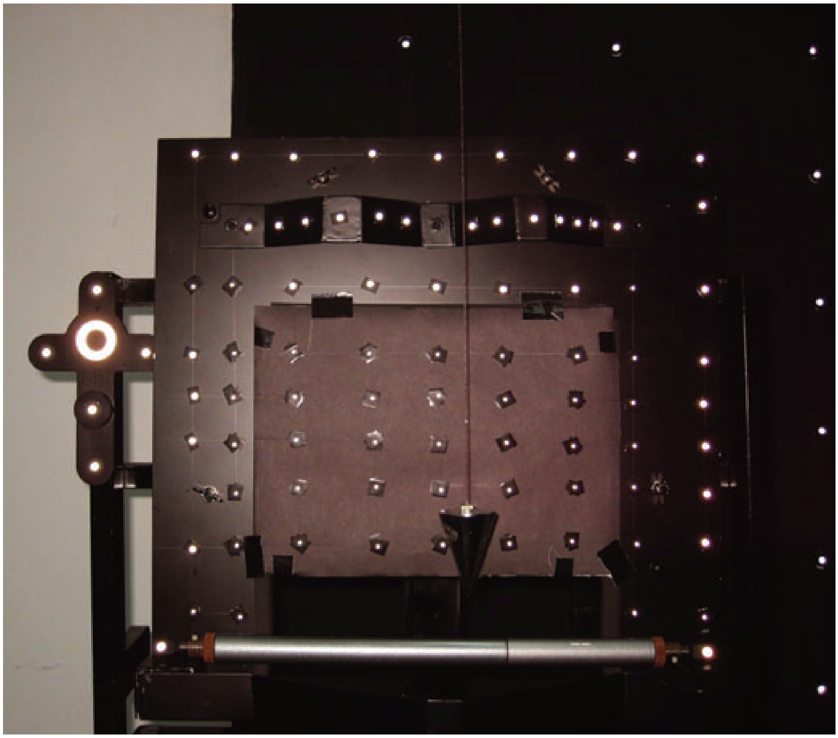

FIG. 6. Camera synchronisation test. A plumb bob was allowed to swing in front of the photogrammetric control frame. Note that a stiff board was placed in the "hole for the patient's head" to provide more targets for photogrammetric relative orientation.
This figure appears in colour in the electronic version of the article and in the plate section at the front of the printed journal.

images and a bundle adjustment on the image coordinates of targets on the photographs (Atkinson, 1996; Fraser, 2000).

Subsequently, the system captures the data of the craniofacial area of the mannequin. The coordinates of the signalised targets on the mannequin are determined from the oriented stereo-image 3D models. The computed coordinates are checked against the coordinates that are obtained by the initial bundle adjustment for any discrepancies or any changes in the error size. Also, the triangulated 3D coordinates of the signalised targets of the mannequin are checked against the control set of coordinates for any discrepancies in the triangulated 3D coordinates.

Operating the Prototype System

Two computers control the prototype system: one operates the three sets of Canon digital stereo cameras while the other operates the two Minolta VI-910 scanning systems. The patient's head is positioned on the headrest. The control frame is positioned around the patient's craniofacial area (Fig. 3). The system console is manoeuvred into position by means of a locking device, which ensures that the object distance of the cameras remains consistent between set-ups. All three sets of stereo cameras are positioned over pre-identified craniofacial areas preceding the photography. Once the images are recorded, the VI-910 systems are activated in succession. As the head of the patient is positioned tightly in a headrest and the patient is directed to stare at a specific point on the console, the position of the head is maintained during the short operation. The prototype and the software are being improved and revised regularly. Consequently, it is difficult to give an accurate time for each set-up. However, the average time required for an adult patient is roughly 20 min. The system will not be used on children until further improvements are made.

Results

Camera Calibration

The results of the camera calibration of the six cameras using Australis camera calibration software are provided in Table I. In the table, it can be seen that the principal point offsets (x_p and y_p) vary considerably between cameras. As the camera-to-object distance and lens setting were set approximately the same (see Figs. 4 and 5) no error was expected from this source.

Results of the Stereo Photogrammetry Test

A DVP digital photogrammetric workstation (DVP-GS, Beauport (Qc) Canada) was used to obtain the coordinates of the pre-signalised targets. The results showed that the photogrammetry technique achieved an accuracy of ±0·5 mm at one standard deviation for any measured distance between two anthropometric landmarks.

Results of Camera Synchronisation Test

Table II shows the mean distance of the plumb bob displacement as a result of non-synchronisation of the cameras' shutters. The stereopair from cameras L2 and L3 provided a reference position. Subsequently, four stereopairs in relation to camera L2 were oriented and the position of the white marker was computed. These stereopairs were denoted as L2–R4, L2–R5, L2–M7 and L2–M8. The x coordinate of the white marker was used to show whether the stereopairs were taken before or after the reference stereopair. The x coordinate could be used for this purpose because the plumb bob moved from left to right across the control board. Subsequently, the displacement would represent either negative or positive time delay.

Table I. The lens parameters of six Canon PowerShot S400 digital professional cameras.

Camera ID	c	x_p	y_p	k_1	k_2	k_3
L2	7·356	−0·037	0·083	2·4E−03	−3·3E−05	−1·3E−07
L3	7·247	−0·003	−0·052	2·5E−03	−2·9E−05	−1·0E−07
M4	7·295	−0·074	−0·065	2·4E−03	−1·2E−05	−9·9E−07
M5	7·232	0·042	0·064	1·8E−03	1·1E−05	1·8E−06
R7	7·262	0·034	−0·022	2·1E−03	−2·3E−06	−1·6E−06
R8	7·151	−0·065	−0·037	1·6E−03	1·1E−04	−7·1E−06

Table II. Results of camera synchronisation test.

Stereopair ID	*L2–L3*	*L2–R4*	*L2–R5*	*L2–M7*	*L2–M8*
Mean distance (mm)	Reference	4·9	0·5	4·5	−4·0
Standard deviation (mm)		1·5	1·2	1·5	2·7
Approximate time delay (ms)		8	0·8	7·5	6·6

A negative delay means the camera shutter opens before L3 and a positive delay means the camera shutter opens after L3. The negative or positive delays were verified by the value of the x coordinate displacement. Equivalence in time for the delay is also provided in the table. Somia et al. (2000) stated that normal eyelids blink at a velocity of about 205 mm s^{-1} and it takes about 0·22 s for the eyelid to complete a cycle. At a velocity of 205 mm s^{-1} a time delay of 8 ms equates to 1·6 mm. No other facial movement has been reported to move at a higher speed. Consequently, the time delay was considered acceptable for the project.

3D Laser Scanning: Minolta VI-910

Fig. 7 shows the output of the scanners. The figure also shows some of the drawbacks of the scanned data, that is, poor texture and occlusions. Test results of the Minolta VI-910

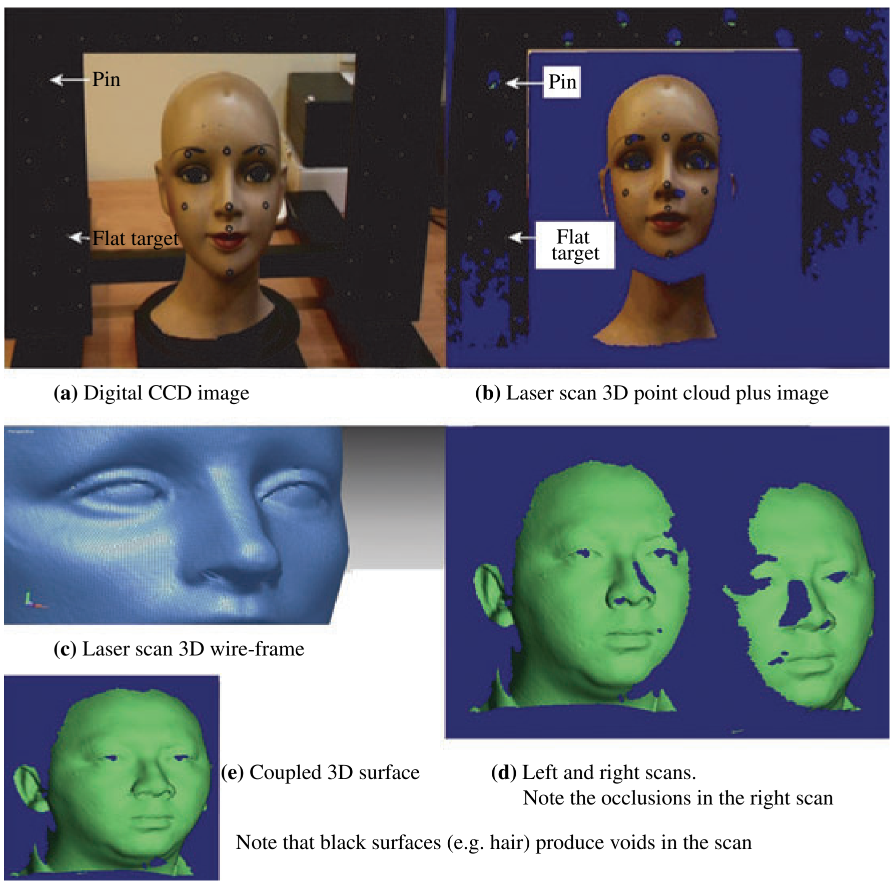

FIG. 7. (a) Left image was captured by a CCD camera. (b) Right image was a representation of the point cloud captured by the Minolta VI-910 laser scanner. (c) Laser scan 3D wire-frame. (d) Scan from the left and right scanner. (e) Scan from left and right scanners were coupled together. Note the contrast between the retro-targets on the "flat" surface and the retro-target on 8 mm diameter pins (varies from 10 to 50 mm in length) in (a) and (b). This figure appears in colour in the electronic version of the article and in the plate section at the front of the printed journal.

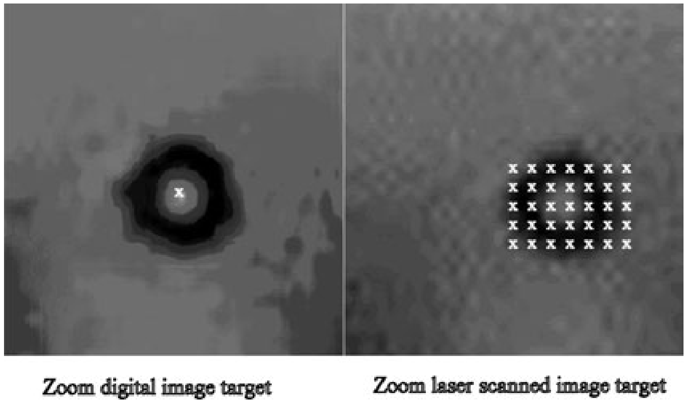

FIG. 8. Left image shows the position digitised by the photogrammetric technique. Right image shows the possible positions which can be digitised on the laser scan.

showed that the system achieved an accuracy of ±0·1 mm, which was close to the current published values. A small sample of the manual registration between the photogrammetric 3D model and scanned point cloud showed an average rms discrepancy of ±0·6 mm. However, the procedure of the registration of the two 3D surfaces required further refinement (Fig. 8). In the figure, one could see the difficulty of selecting the correct point amongst the point cloud in the scanned 3D model. In addition, the accuracy for living craniofacial features was significantly reduced as a result of patient movement, especially for the younger population. Laboratory tests with two living subjects showed that the accuracy was of the order of ±1·2 mm because of facial movement during data capture.

DISCUSSION

A number of problems have been encountered in the project so far. Some have been solved while others are being worked on. Initially, the problems involved synchronising eight digital cameras. The problem was solved when more advanced off-the-shelf medium-resolution digital cameras appeared on the market and Graphic Media Research, Cannon Falls proved able to produce a synchronisation device for up to eight cameras for the project. The next problem involved the positioning of the patient's head in the headrest. Having a reference mark on the system console, which the patients could focus their eyes on during the photography and 3D laser scanning, solved the problem. Other problems involved stereo digitising and laser 3D scan editing. Proper training and customising software were the main reasons. Tackling these problems requires much longer time and a lot more effort. At present, a team of seven M.Sc. and four Ph.D. students, technicians and programmers are involved in resolving these problems.

The prototype system is suitable for the capture of the planned 3600 young and adult patients. For the system to be infant-friendly, it will require a few structural changes, namely: (1) the size of the chair, (2) the location of the cameras and the laser 3D scanners, and (4) the lighting. Consequently, the option is to build a smaller console for infants.

The system was designed for use by medical lab technicians. The research phase should be completed by 2005. Medical lab technicians would be given the tasks of taking the stereo photographs and running the laser 3D scanners. Medical Imaging Research Group (MIRG) technicians at the Universiti Teknologi Malaysia campus would process the stereo photographs and the laser 3D scans. In addition the MIRG would employ data entry personnel to populate the craniofacial database.

CONCLUDING REMARKS

In the paper, the use of digital photogrammetry and 3D laser scanning technology has been discussed for the spatial data capture of craniofacial features. Matters concerning the type of spatial data needed for a national database and the particulars relating to the design of an accurate stereo-imaging and 3D laser scanning system have also been discussed. In addition, a short discussion was provided on the procedure concerning the quality control of the data captured by the photogrammetric/3D laser scanning system. Also, test measurements showed that the accuracy met the specifications for craniofacial data capture for the database.

While the cost of the system is high because of the introduction of the 3D laser scanning technology, it is believed the initial cost is easily offset by the high labour cost for 3D surface model generation using the conventional stereo-image matching photogrammetric technique and the time involved in the process. The system requires a minimum time to populate the national database with quality data.

Research is in progress to customise software and to optimise the stereo digitising and 3D laser scan editing techniques. In addition, tests are being carried out on the use of natural points for joining stereomodels and an advanced electronic device for camera/scanner synchronisation. The results of the research will be published in the near future.

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Résumé

La photogrammétrie se présente comme une technique rentable, pratique, de haute précision, sans contact avec l'objet, valable pour un grand nombre d'applications médicales. Dernièrement les techniques à base d'images numériques ou de balayage 3D par laser ont accru l'intérêt et l'importance de la photogrammétrie numérique pour la cartographie de la boîte crânienne. Le Ministre de la Science, de la Technologie et de l'Environnement de Malaisie (MOSTE), dans le cadre du 8ème plan malaisien de Développement, a accordé une subvention pour définir les procédures d'établissement d'une base de données 3D nationale sur la boîte crânienne, et permettre au corps médical de fournir de meilleurs soins de santé *à la population. Pour alimenter cette base de données en données crâniennes normales et anormales (venant de victimes de brûlures, traumatismes, maladies ou malformations), il faut évaluer d'abord les technologies nécessaires à la saisie des principales données caractérisant la boite crânienne.*

On examine dans cet article les éléments de base relatifs à ces données 3D et aux techniques de saisie, l'ensemble des deux étant nécessaire pour établir cette base de données 3D nationale sur la boite crânienne. On analyse rapidement l'état actuel des deux techniques èvoquées ci-dessus, à savoir la photogrammétrie numérique et le balayage 3D par laser. On s'attache dans cet article au système mis en œuvre dans le cadre du projet malaisien de cartographie crânienne.

Les essais en laboratoire avec des mannequins ont montré que le système de photogrammétrie et de balayage laser utilisé pouvait fournir une précision supérieure aux spécifications affichées de ±0.7 mm (écart-type), sur toutes les distances mesurées sur la boite crânienne. Toutefois les essais sur des êtres vivants ont montré que la précision tombait à environ ±1.2 mm, à cause des mouvements qui se présentaient en cours de saisie.

Zusammenfassung

Die Photogrammetrie ist ein berührungsloses, hochgenaues, zweckmäßiges und kostengünstiges Verfahren für eine große Anzahl medizinischer Anwendungen. Durch das 3D Laserscanning und digitale Aufnahmetechnologien hat die Bedeutung der Digitalen Photogrammetrie für die Modellierung von Schädel- und Gesichtsoberflächen stark zugenommen. Mit Unterstützung des Achten Malaysischen Entwicklungsplans wurde vom Ministerium für Wissenschaft, Technologie und Umwelt (MOSTE) in Malaysia ein Projekt zur Entwicklung von Verfahren für die Aufstellung einer nationalen Gesichts- und Schädeldatenbank eingerichtet. Diese Datenbank soll die Medizin bei der Bereitstellung verbesserter Gesundheitsdienste unterstützen. Die Datenbank soll mit Informationen über normale und abnormale Schädel- und Gesichtsoberflächen gefüllt werden. Letztere können durch Missbildungen, durch Erkrankungen, Verletzungen oder Verbrennungen hervorgerufen werden. Es ist absolut erforderlich die Technologie zu evaluieren, die es erlaubt die wesentlichen Daten von Gesichts- und Schädeloberflächen zu erfassen. Dazu dient dieser Beitrag, der sowohl die räumlichen Daten zur Modellierung als auch die Datenerfassungstechniken vorstellt. Die Diskussion beinhaltet eine kurze Analyse des aktuellen Standes zweier hochgenauer Techniken, nämlich der digitalen Photogrammetrie und dem 3D Laserscanning. In dem Beitrag wird ein System besonders hervorgehoben, dass in dem malaysischen Projekt entwickelt wurde. Laboruntersuchungen mit Schaufensterpuppen haben gezeigt, dass dieses System, gestützt auf Photogrammetrie und Laserscanning, eine Genauigkeit von ±0.7 mm (Standardabweichung) für alle gemessenen Distanzen im Bereich des Schädels, bzw. Gesichts erreicht, was die Erwartungen übertraf. Jedoch haben Versuche mit lebenden Personen gezeigt, dass die Genauigkeit nur noch im Bereich ±1.2 mm lag, was auf Gesichtsbewegungen während der Aufnahme zurückzuführen war.

Resumen

La fotogrametría es una técnica sin contacto, de alta precisión, económica y práctica para un gran número de aplicaciones médicas. En los últimos tiempos, las *tecnologías de imágenes digitales y de escaneado láser en 3D han acrecentado la importancia de la fotogrametría digital en el campo de la cartografía craneofacial. Con el apoyo del Octavo Plan Malayo de Desarrollo del Ministerio de Ciencia, Tecnología y Medio Ambiente (MOSTE), Malasia ha proporcionado financiación para establecer unos procedimientos para el desarrollo de una base de datos espacial craneofacial nacional, ayudando así a la profesión médica a proporcionar mejores servicios de salud a la población. Con el objeto de almacenar en la base de datos información craneofacial tanto de casos normales como anormales (víctimas de malformaciones, epidemias, traumas y quemados), se hace necesario evaluar la tecnología necesaria para capturar los datos esenciales de los rasgos cranefaciales.*

El artículo examina las características básicas de los datos espaciales y las técnicas de captura de datos. Ambos son necesarios para establecer una base de datos craneofacial espacial nacional. El examen incluye una breve revisión del estado actual de la fotogrametría digital y el escaneado láser 3D, las dos técnicas seleccionadas para la captura de datos espaciales de alta precisión. El artículo describe un sistema que ha sido desarrollado por un proyecto malayo de cartografía craneofacial.

Las pruebas de laboratorio con maniquíes demostraron que nuestro sistema fotogramétrico y de escaneado láser 3D puede alcanzar una exactitud que supera la especificación de diseño de ±0.7 mm (una desviación típica) para todas las distancias craneofaciales medidas. Sin embargo, los ensayos realizados con dos personas mostraron que la exactitud estaba en el orden de ±1.2 mm, un valor más alto que es resultado del movimiento facial durante la captura de los datos.

ZULKEPLI MAJID

Faculty of Geoinformation Science & Engineering, University Teknologi Malaysia.

ALBERT CHONG

School of Surveying, University of Otago, Dunedin.

HALIM SETAN

Faculty of Geoinformation Science & Engineering, University Teknologi Malaysia.

Calibrating Minolta VIVID 910 3D laser scanner for medical mapping

ABSTRACT

The paper describes the calibration of a Minolta Vivid 910 3D laser scanner for medical applications such as denture, trunk, limb and craniofacial (face and skull) 3D mapping. The calibration of the scanner was essential to determine the accuracy and reliability of the instrument. The Vivid 910 was calibrated using three objects of different shape, size and surface texture. The objects used were: 1) a smooth-surface cylinder; 2) a dental cast; and 3) a mannequin. Each object was scanned five times and was later measured using close-range photogrammetry technique and/or a Microscribe 3D electronic digitiser system. The measurements obtained by the scanner were compared with the measurements obtained by the other two techniques. In addition, the close-range photogrammetry measurements were held as the true values. The results show that the scanner has accuracies ranging from 0.1- 0.3mm at one standard deviation depending on the shape, size and surface texture of the objects.

ZULKEPLI B. MAJID – MSc (UTM) is a co-director of the Medical Imaging Research Group (MIRG) at the Faculty of Geoinformation Science and Engineering, Universiti Teknologi Malaysia, Johor, Malaysia. He specialises in digital photogrammetry and 3D laser scanning technology for bio-medical imaging applications. Currently, he is completing his PhD in bio-medical imaging for craniofacial soft tissue mapping.

ALBERT K. CHONG – B Sc. (Cal. State Fresno), Ph.D. (Washington) is a senior lecturer at School of Surveying, University of Otago. He completed his Ph.D. in Photogrammetry at the University of Washington, Seattle.

Albert's current major research interest is in the field of medical photogrammetry: 1) craniofacial mapping; 2) effect of rigorous exercise on spinal cord; 3) MRI and NIR spectroscopy for cancer detection; and 4) swallowing coordination

DR. HALIM SETAN is a professor at the Department of Geomatic Engineering, Faculty of Geoinformation Science and Engineering, Universiti Teknologi Malaysia. He holds a B.Sc. (Hons.), M.Sc., and a Ph.D.

His current research interest is in 3D modeling and measurement, deformation monitoring, least squares estimation and industrial metrology.

INTRODUCTION

The paper discusses the calibration of the Minolta Vivid 910 Laser scanner (Konica Minolta, Japan) for medical mapping. Generally, the scanning system consists of a red laser light source, a light projection system and a digital imaging system. A set of prisms and mirrors projects the Laser beam as an ultra-thin profile on the object, which is photographed by a CCD camera mounted close to the projector (Figure 1). The relative position between the internal reference point of the projection system and the camera lens is fixed. In addition, the angle of each projected laser profile plane and the angle of the camera optical axis were calibrated in advance. Subsequently, the x, y and z coordinates of the object-space position of each pixel on the object can be computed using the scale of the photography, the relative positional vector and the known angles. A least squares technique is used to compute a set of optimal 3D coordinates of the object surface. By and large, the texture and radiometric value of the CCD images are added to the 3D data to obtain a realistic 3D surface model of the object. Further information of the scanner design and specifications can be found in O'Grady and Antonyshyn (1999) and Bernardini et al (2001).

The scanner is fully supported by a suite of software, which includes limited system calibration, data capture and data editing. The data capture phase is fully automated. After conducting a scan, the 3D point cloud may be displayed and edited on the computer screen using third party software such as RapidForm (INUS Technology Inc. Soul Korea).

In the paper, the Vivid 910 was calibrated using three objects of different shape, size

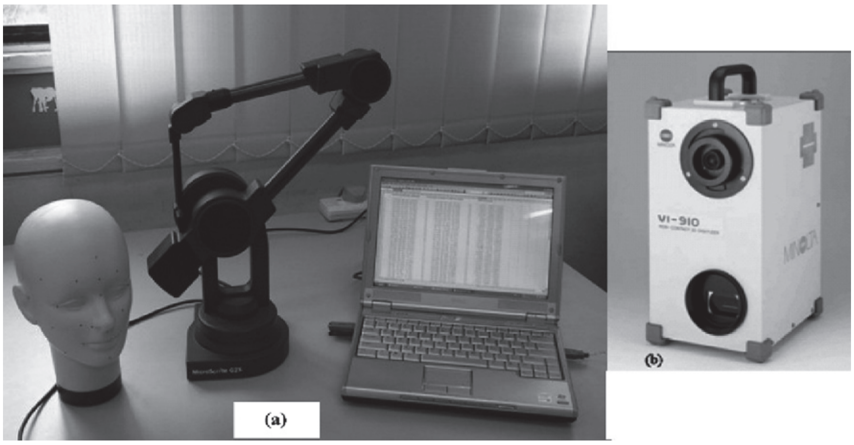

Figure 1: a) Microscribe 3D digitiser and b) Minolta Vivid 910 Laser scanner.

and texture: 1) a small cylinder; 2) dental cast; and 3) a mannequin. Subsequently, the objects were measured by close-range photogrammetry technique and a Microscribe 3D electronic digitizer system (Immersion Corporation, San Jose, CA) where applicable. The measurements obtained by the scanner were compared with the measurements obtained by both the close-range photogrammetry and Microscribe 3D digitizer system (Figure 1). The close-range photogrammetry measurements were selected as true values.

METHODS AND MATERIALS

Scanning the cylindrical object

A cylindrical object of width of 120mm and height of 196mm was chosen because of the simplistic curve-shape and smooth surface (Figure 2). The object was scanned five times and the averaged width and height were computed.

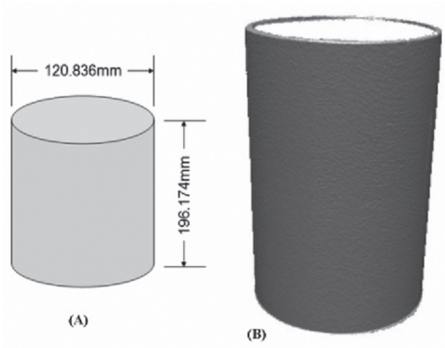

Figure 2: The cylindrical object: (A) is Drawing and (B) Laser Scan.

Scanning the dental cast

The dental cast was positioned at 650mm (S_d = 650mm) from the scanner (Figure 3). A telephoto lens (focal length = 25 mm) was used as the dental cast was small compared to regular objects as a human trunk. To build a complete 3D model two scans were required and the optical axis of the scan were set roughly to 25 degrees from the central line as shown in the figure.

After the scanning, pre-processing involved a 3D registration of the two scans (known as shell) to build a complete 3D model. The registration method uses a reverse engineering method programmed into the RapidForm 2004 3D modelling software (INUS Technology, Seoul, South Korea). Five corresponding points was measured manually on the left shell and the right shell respectively. After digitizing the five points, the registration proceeded automatically. Figure 4 shows the 3D registration process.

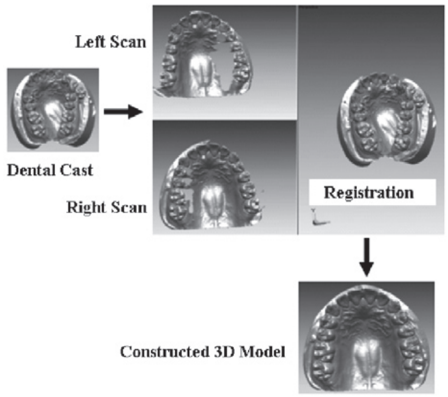

Figure 4: 3D shell/shell registration using Rapidform Software.

The accuracy of the 3D registration process was analyzed using shell/shell deviation method. The method calculated the deviation value between the left shell and right shell dental in the overlapping area of the dental cast. The deviations between the shells are displayed in colour scale method (Figure 5). The colour scale shows the registration accuracy was close to 0.1mm (average value of deviation).

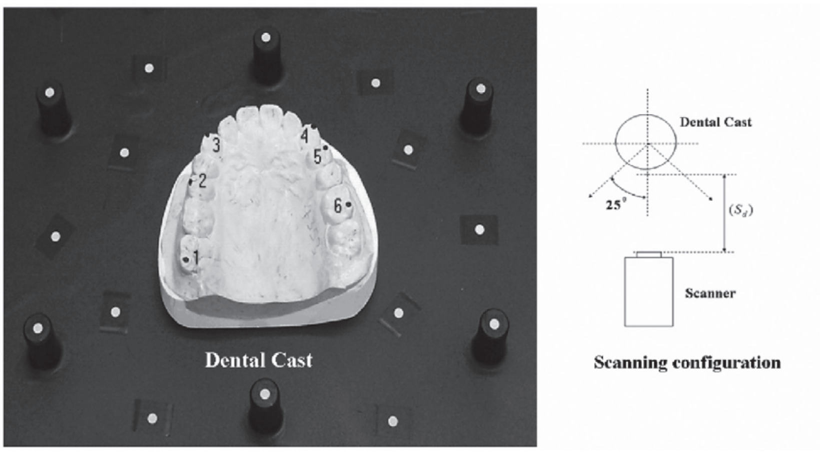

Figure 3: The dental cast and the scanning configuration.

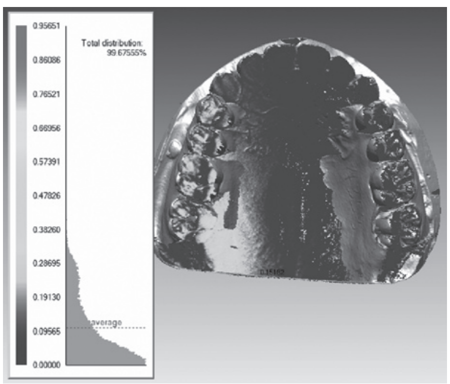

Figure 5: Shell/Shell deviation analysis of rebuilt dental cast surface model.

The final step in the processing of the scans is the 3D merging process. The 3D merging process could be executed if the accuracy of the 3D registration of the left shell and the right shell was within the accuracy required for the project. The accuracy required for the mapping project was 0.7mm and the value was larger than the 3D registration accuracy (0.1mm). Again, the 3D merging process was carried out using RapidForm software. The merging process involves combining the two overlapping shells into one shell or one 3D surface model. Figure 6 shows the merged dental cast model.

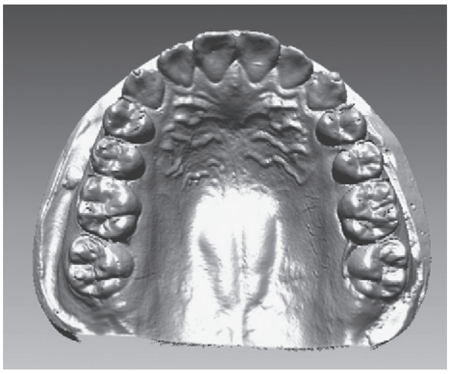

Figure 6: Merged 3D dental cast.

The accuracy of the 3D dental cast was evaluated by a comparison of the slope distances between anatomical dental points. Six anatomical dental points were selected (Figure 2). Ten slope distances was measured on the 3D model using point-to-point distance measurement function (RapidForm software). The average slope distances obtained from five constructed models were compared with the distances from convergent photogrammetric technique and the Microscribe 3D electronic digitizer system. Figure 7 shows an example of the slope distance measurement on the dental cast surface 3D model.

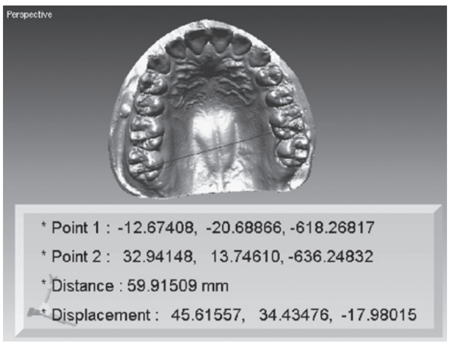

Figure 7: Slope distance measurement on dental cast surface 3D model.

Scanning the mannequin

The mannequin and the scanner were positioned as shown in Figure 8. Nine anthropometric marks were placed on the mannequin so that slope distances could be obtained from the scanned model for accuracy comparison. The mannequin was scanned three times and each time both the left and the right scans were captured as shown in Figure 8.

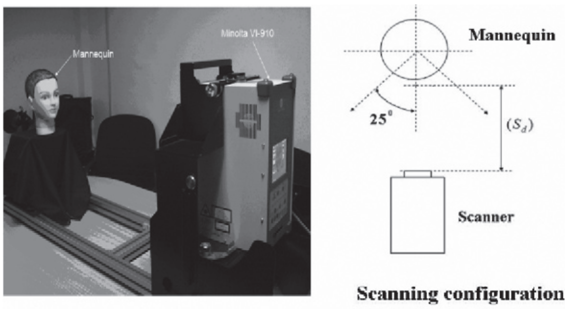

Figure 8: The mannequin and the scanner during the scanning. Note that the holding device can rotate the scanner along it vertical axis.

Photogrammetry technique

As mentioned elsewhere in the paper, measurements from the photogrammetric technique were selected as the true values. Consequently, it is essential to provide a short discussion as to the method of imaging, data capture and accuracy analysis of this technique. The object provided is based on the dental cast which is considered difficult to map because of its size. The dental cast was placed on top of a calibration range as shown in Figure 9. The range consists of retro-targets which can be digitised to one-hundredth of a pixel. The range was calibrated before the exercise (Chong 1999). Three sets of six-convergent images was captured and processed using Australis bundle adjustment software (Photometrix Pty Ltd, Kew, VIC. Australia). The average of the 3D coordinates of the anatomical dental points was used to calculate the distances between the points (Figure 3).

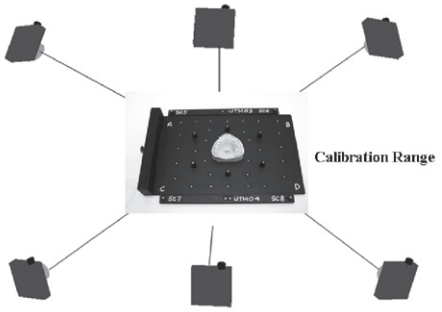

Figure 9: Measurement of dental cast using convergent photogrammetric method.

RESULTS AND ANALYSIS

The cylindrical object

The computed difference and standard deviation based on five sets of measurements are provided in Table 1. The standard deviation is within the limit of 0.7 mm as required by our medical mapping project.

Table 1: Measured and true dimension of the cylinder.

Dimension	Averaged dimension (mm)	True dimension (mm)	Difference (mm)	Standard Deviation (mm)
Height	196.591	196.174	0.366	0.191
Width	120.325	120.836	0.511	0.203

The dental cast

Table 2: Slope distance comparison between three measurement techniques.

Slope Distance	Scanner (mm) (A)	Photogrammetry (mm) (B)	Microscribe (mm) (C)	A-B (mm)	A-C (mm)
5-6	20.769	20.552	20.510	0.217	0.259
5-1	60.793	60.637	60.601	0.156	0.192
5-2	49.503	49.484	49.585	0.019	-0.082
5-3	42.919	42.865	42.929	0.054	-0.010
4-3	38.261	38.399	38.414	-0.138	-0.153
6-1	60.128	59.637	59.680	0.491	0.448
6-2	56.903	56.653	56.798	0.250	0.105
6-3	55.805	55.715	55.938	0.090	-0.133
2-3	17.161	17.257	17.102	-0.096	0.059
1-1	24.353	24.140	24.124	0.213	0.229
			Mean	***0.172***	***0.167***
			Std Dev.	***0.128***	***0.119***

Table 3: Slope distance comparison between photogrammetry and scanner.

Slope distance	Photogrammetry (mm) (A)	Scanner (mm) (B)	A-B (mm)
3-5	51.010	50.817	0.193
4-6	64.009	64.122	-0.113
3-7	105.197	105.464	-0.267
5-7	105.366	105.613	-0.247
3-2	83.003	83.079	-0.076
5-9	88.703	88.750	-0.047
		Mean	***-0.093***
		Std. Dev	***0.166***

The results of dental cast study show that there were no significant differences statistically between the three measurements (Table 2). All three techniques satisfied our project accuracy of requirement 0.7 mm at one standard deviation. However, the scanner is a very efficient method of capturing the 3D surface of the dental cast.

The mannequin

The results of the study on mannequins show that the differences and standard deviations were also within the limit required for our medical project (Table 3). In this case, measurements obtained by the photogrammetric technique were held as the true values.

DISCUSSION AND CONCLUSION

The calibration was carried out for three reasons: 1) the scanner can give the accuracy we needed for various types of object shape, object size (from size of the trunk to size of a finger nail) and surface texture; 2) our processing method gives the correct measurement; and 3) we would have calibration data to show our mapping products are accurate within the project specifications. In general, our models were computed based on an arbitrary coordinate system which made it difficult to compare the scan measurements with other techniques such as photogrammetry. Consequently, we computed and used slope distance in the comparison.

The results of the study show that Minolta Vivid 910 3D laser scanner satisfies the accuracy required for our medical mapping project. In addition, the time required to produce a 3D surface model is a fraction of the time it takes to produce a similar model using photogrammetric technique. Because the scanner does not freeze the scene as in the case of photogrammetry technique, movement of human subject can be problematic. Limited tests showed that the error of movement can result in the rejection of the many scanned models in craniofacial mapping.

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4		
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