

3D SURFACE RECONSTRUCTION FOR LOWER LIMB PROSTHETIC MODEL
USING MODIFIED RADON TRANSFORM

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Biomedical Engineering)

Faculty of Biosciences and Medical Engineering
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AUGUST 2017

Dedicated especially to my beloved late father, Mohd Sobani bin Bahrom,
my beloved late mother, Siti Zabedah binti Ab. Hamid,
also family and friends.

ACKNOWLEDGEMENT

Praise to Allah S.W.T, the Most Gracious, the Most Merciful, for blessing and guidance that always helped me through my life. I am so fortunate to be given the opportunity and strength to live and to accomplish the Ph.D project. The pleasure to be able to breath until the day that I finished this book of thesis.

In particular, I wish to express my sincere appreciation to my supervisor, Assoc. Prof. Dr. Nasrul Humaimi bin Mahmood then, and my co-supervisor, Dr. Nor Aini binti Zakaria for their wisdom, critics and advices. I am thankful to their guidance to the success of this study. Without their continuous supports and interests, this thesis would not have been the same as presented here.

My sincere appreciation also extends to all my family and colleagues who have provided assistance at various occasions. Their views and tips are useful indeed. Unfortunately, it is not possible to list all of them in this limited space. I am grateful to all my beloved family members whom without their constant support and encouragement, I would not be able to make it this far.

ABSTRACT

Computer vision has received increased attention for the research and innovation on three-dimensional surface reconstruction with aim to obtain accurate results. Although many researchers have come up with various novel solutions and feasibility of the findings, most require the use of sophisticated devices which is computationally expensive. Thus, a proper countermeasure is needed to resolve the reconstruction constraints and create an algorithm that is able to do considerably fast reconstruction by giving attention to devices equipped with appropriate specification, performance and practical affordability. This thesis describes the idea to realize three-dimensional surface of the residual limb models by adopting the technique of tomographic imaging coupled with the strategy based on multiple-views from a digital camera and a turntable. The surface of an object is reconstructed from uncalibrated two-dimensional image sequences of thirty-six different projections with the aid of Radon transform algorithm and shape-from-silhouette. The results show that the main objective to reconstruct three-dimensional surface of lower limb model has been successfully achieved with reasonable accuracy as the starting point to reconstruct three-dimensional surface and extract digital reading of an amputated lower limb model where the maximum percent error obtained from the computation is approximately 3.3 % for the height whilst 7.4%, 7.9% and 8.1% for the diameters at three specific heights of the objects. It can be concluded that the reconstruction of three-dimensional surface for the developed method is particularly dependent to the effects the silhouette generated where high contrast two-dimensional images contribute to higher accuracy of the silhouette extraction. The advantage of the concept presented in this thesis is that it can be done with simple experimental setup and the reconstruction of three-dimensional model neither involves expensive equipment nor require any service by an expert to handle sophisticated mechanical scanning system.

ABSTRAK

Bidang teknologi komputer kini memberi fokus yang tinggi kepada kajian dan inovasi mengkonstruksi permukaan tiga-dimensi yang lebih tepat dan konsisten. Walaupun telah banyak penyelidik berjaya menemukan pelbagai penyelesaian baharu dalam bidang ini, namun kebanyakannya dihasilkan dengan menggunakan peranti canggih yang mahal. Langkah-langkah penyelesaian untuk penambahbaikan harus dikenal pasti dengan mengarang algoritma baharu yang berupaya untuk menghasilkan keputusan dalam masa yang lebih singkat dan juga mengambil kira penggunaan peranti mampu milik. Oleh itu, tesis ini menghuraikan idea penghasilan model tiga-dimensi kaki kudung menggunakan teknik pengimejan tomografi dengan strategi yang diterima pakai berkaitan penglihatan kamera dalam pelbagai pandangan dan meja berpusing. Permukaan sesebuah objek dikonstruksi semula daripada imej-imej dua-dimensi diperolehi daripada 36 unjuran yang berbeza tanpa ditentu-ukur dengan menggunakan algoritma transformasi Radon dan juga bentuk-dari-bayang. Keputusan kajian membuktikan bahawa kaedah yang dicadangkan dalam tesis ini untuk mengkonstruksi permukaan tiga-dimensi sesebuah model kaki kudung telah berjaya mengkonstruksi permukaan tiga-dimensi dan mendapatkan ukuran digital sesebuah model kaki kudung dengan ketepatan yang munasabah sebagai permulaan untuk mengembangkan bidang kajian ini dengan menganalisis ralat dalam pengiraan yakni peratus tertinggi yang diperolehi adalah 3.3% untuk ukuran ketinggian manakala 7.4%, 7.9% dan 8.1% untuk tiga diameter pada ketinggian tertentu. Bagaimanapun, kaedah yang dicadangkan amat sensitif kepada imej bayang yang dihasilkan menunjukkan bahawa imej berkontras tinggi menyumbang kepada ketepatan dalam menghasilkan imej bayang. Projek ini dapat dilaksanakan secara ringkas dengan penyusunan alat-alat eksperimen yang mudah dan tidak memerlukan mana-mana mesin yang memakan kos yang tinggi atau pengendalian oleh individu yang pakar.

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LIST OF ABBREVIATIONS

1D	-	One-dimensional
2D	-	Two-dimensional
3D	-	Three-dimensional
CAD	-	Computer-aided Design
CAM	-	Computer-aided Manufacturing
CIRBM	-	Combination of Image and Range-based Modelling
CT	-	Computed Tomography
DOF	-	Depth of Field
FOV	-	Field of View
IBM	-	Image-based Modelling
IBR	-	Image-based Rendering
JPEG	-	Joint Photographic Experts Group
MHD	-	Modified Hausdorff distance
MRF	-	Markov Random Field
MRI	-	Magnetic Resonance Imaging
MSE	-	Mean squared error
PNG	-	Portable Network Graphics
POI	-	Point of interest
PSNR	-	Peak signal-to-noise
RAM	-	Random-access Memory
RBM	-	Range-based Modelling
RGB	-	Red-Green-Blue
RT	-	Radon Transform

LIST OF SYMBOLS

$^{\circ}$	-	Degree of angle
θ	-	Angle
%	-	Percent
<i>bit</i>	-	Basic unit of digital information, binary digit
<i>cm</i>	-	Unit of length, centimeter
<i>dpi</i>	-	dot per inch
<i>f</i>	-	focal length
<i>GB</i>	-	Unit of digital information, gigabyte
<i>GHz</i>	-	Unit of frequency, hertz
<i>mm</i>	-	Unit of length, millimeter
<i>ppi</i>	-	pixel per inch

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CHAPTER 1

INTRODUCTION

1.1 Project Backgrounds

Amputation is the removal of all or certain part of a limb from one body through surgical operation. Limb or extremity is classified into two parts which are upper and lower limbs, also known as the arms and the legs. There are several unfortunate causes that encourage an amputation such as loss from severe trauma or to supplement defective body parts due to either serious illness or infections. For example, lower limb amputation of a diabetic patient to prevent the infection from spreading all over his body, because the high blood sugar level has damaged the nerves of the patient and reduced the sensation on his feet, which may become injured or develop foot ulcers without one realizing the situation. Injury damaging the blood vessel contributes to reduction of the blood supply to the feet and causes the wound to take longer time to heal and get infected. Amputation cases have occurred every year worldwide and millions of individuals currently live in unfortunate lives with limb loss, many of which are cases where amputations are at the lower limb. In medicine, an artificial device used to replace amputated body parts of a person either from amputation or birth defects is known as a prosthesis or prostheses in plural. The term “prosthesis” is originated from the Greek word, where “pro” means “in place of” and “thesis” means “the action of placing” [1]. Figure 1.1 illustrates the meaning of the

prosthesis. Some amputees choose to continue their daily activities by wearing an artificial device called prosthesis that requires them to face the challenge in the process of rehabilitation. The prostheses have to be designed and customized specific to one's anatomical shape. Hence, the design cannot be simply designed and manufactured through mass production or modular products since it is specific to each person, and each individual is different from another. However, as the number of amputees increase, the demand on prostheses has also increased and it is necessary to realize ad-hoc and high precision design methodologies [2, 3] as a proper guideline to be referred by prosthetists. A prosthetist is a person who specializes in the detailed measuring, designing, fabricating and fitting of prosthesis prescription. In addition, optimal design of prosthesis is very important for each amputee. This restores and encourages functional muscular activity, relieves pressure-sensitive areas, and maintains proper attachment of the prosthesis during ambulation [4].

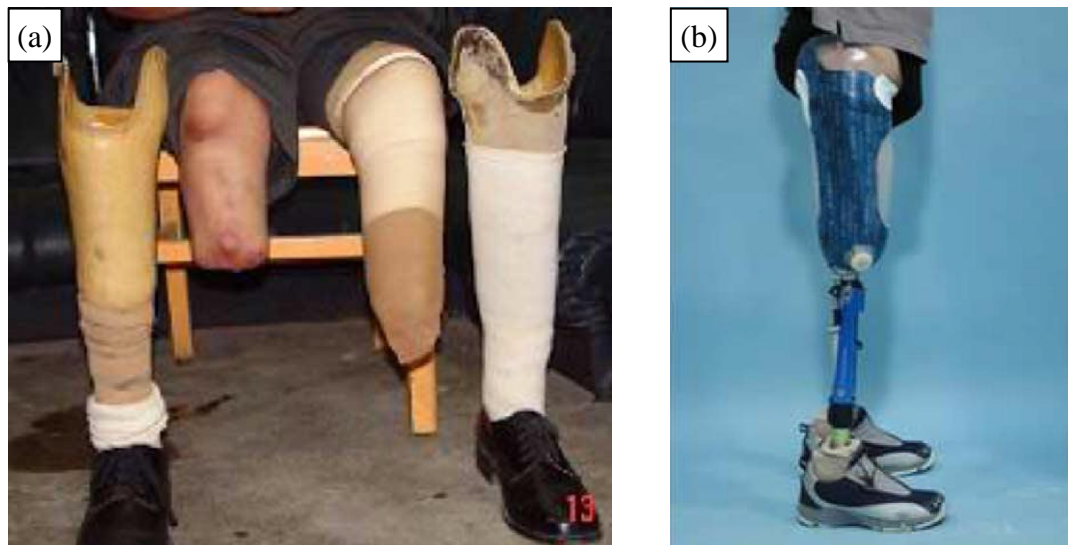


Figure 1.1: Example for (a) a patient with residual limb below the knee [5], and (b) trans-femoral prosthesis [3].

Today, technological developments of three-dimensional (3D) imaging are highly sophisticated, centered on the digital models of the human body and the use of 3D reconstructive prosthetic design through the reconstruction of 3D surfaces of the residual limb, which have overcome the limitations of the plaster-casting method in traditional prosthetic socket fabrication. Furthermore, it provides a scientific basis for

the individualization of prosthetic design and avoids making a positive mould in manual modifications for prosthesis fitting [6, 7]. In 3D reconstruction, there are two different systems known as calibrated and uncalibrated systems. Calibration is an initialization step required in data acquisition system that provides corresponding information between real world's coordinates and two-dimensional (2D) image coordinates. Consequently, the image acquisition devices are restricted to fixed locations after the calibration is done, while this process is not required for uncalibrated systems. As an alternative, 3D reconstruction is achieved by extracting information from digital images to infer particular features for corresponding coordinates and 3D structure of an object. The image data can be acquired in several forms, such as a set of image sequences or a video, views from multiple cameras set up, or multi-dimensional data from a scanner. Prior research has sought and demonstrated various methods to realize an accurate 3D reconstruction of a surface aiming to assist the prosthetist in designing a proper prosthetic part for a specific patient to recover and live a normal daily life. Various methods have been introduced to improve the quality of 3D image reconstructed and acquisition time of the system and application. Computer-aided design and computer-aided manufacturing (CAD/CAM) accompanied with medical imaging technology has been introduced in prosthetic practice [8] where the image of a certain part of a patient is captured using X-ray computed tomography scan (CT-scan), magnetic resonance imaging (MRI), or ultrasound imaging [9, 10]. However, capturing images using such devices are very expensive and the processing task requirements are enormous. The medical device is also required to be operated by an expert in a specifically designated room. It is also bulky and taking up a large space to be assembled. The outcome from this project is expected to be able to compute and overcome possible constraints in the production of prosthetic part which is practically cost-efficient.

As the first step in a research, it is necessary to determine a possible method and compare with other existing methods related to 3D surface reconstruction of amputated lower limb models. 3D reconstruction in computer vision field is a process of recovering and converting the shape and appearance of an object into digital data form or so called 3D model to be effectively manipulated in virtual world [11]. 3D models are mostly realized from detailed information of an object as input data. The input data can be acquired either by active or passive sensing method which both are

non-contact system based on illuminations [12, 13]. Active sensing method or also known as range data method is a sensing and scanning technique that actively interfere with the object to be reconstructed to pick up the depth map of the scene. Active sensor provides range data with the 3D coordinates covering the point cloud which usually defined by x , y and z coordinates represent the external surface of an object. Examples for 3D scanning technology established are time-of-flight laser range finder, structured light, and modulated light scanner [14-16]. Even though these 3D scanners are mostly high quality in capturing detailed information that contributed to high accuracy in the measurement of the reconstructed 3D surface, unfortunately active sensing method is not always viable for modelling distant or huge or fast-moving objects [17, 18]. There are few other limitations on encountering optical difficulties with transparent, shiny, and reflective objects which is not desirable in some cases for 3D reconstruction for example, human recognition applications, plus they are very disadvantageous in term of cost efficiency [19]. On the other hand, the passive sensing method is relatively low cost and the research on this method has been intense recently. Although passive sensing method not as efficient as the active sensing method in the reconstruction quality and accuracy, its non-intrusive properties is more reliable for robotic vision, reconnaissance, surveillance, recognition applications. Passive sensing method in 3D reconstructions does not interfere with the object which only measure the illumination emitted or reflected on the object in the scene in order to process, analyse, and acquire the 3D structure of an object [20-22]. Passive sensor provides image data as the impression of an object that needs further processing on the images to locate and originate the 3D coordinates. Generation of meshes connect the 3D coordinates and constructs a polygonal surface of the object. The polygonal surface is then textured and shaped to realize 3D surfaces of the object. Therefore, this project aims to reconstruct 3D surface of lower limb models based on the passive approach where the input data is 2D image sequences of amputated lower limb models captured by multiple-view camera and a turntable setup in specified projections as the first step in adapting to the research field.

1.2 Problem Statements

Although many researchers have come up with various novel solutions and some even proved the feasibility of their findings, most require sophisticated devices. Research for prosthetic design by [5] has successfully reconstruct 3D structure of residual limbs with $0.01mm$ accuracy by using CT-scanning device for data acquisition, but costed a lot and may not be affordable to some amputees. It is also computationally complex which took eighteen hours of processing time for a skilled operator compared to the traditional process that took twelve hours to build a solid model but resulted to slightly higher error which is $0.25mm$. A suitable algorithm has to be configured for 3D surface reconstruction in order to resolve the reconstruction constraints which involves huge amount of data which consumes a lot of time to compute the whole process and also computational expensive. Thus, a proper countermeasure is needed to resolve the reconstruction constraints and create an algorithm that is able to do considerably fast reconstruction by giving attention on devices available with appropriate specification, performance and also practically affordable.

Passive methods is indeed cost-effective and for example, it has been proposed in [7] that 3D surface reconstruction from digital images taken in multiple-views with turntable system also yields significant low errors in the measurements. In medical imaging, tomography is a technique that display layers of cross-section of a part of human body estimated from a finite number of projections [23, 24] which provide multiple-views of an object and it is often relates with Radon transform algorithm. Another research which is also cost-effective by [25] has shown that reconstruction of 3D surface from Radon transform algorithm can be achieved by using a digital camera as the device for data acquisition. However, the data acquisition was done in a completely dark environment where a light beam is projected onto the object providing a substantial contrast between the object and the background. It is not a good idea to deal with an object in a dark room where grain noise may present in the image captured. Plus, taking 2D images using a turntable setup is actually quite a challenging task and is practically inefficient to perform the data acquisition in a dark room, so it is suggested to capture the images in a well-lighted area instead.

Thus, the method for this thesis is focused on passive sensor to generate surface of an amputated lower limb model using 2D image sequences as the input data without any complicated calibration performed on the digital camera to simplify the data acquisition process. In addition, the concept of tomographic imaging is adopted to construct layers of cross-sections of an object to recover possible obscured side curve of the object from the camera view. 3D reconstruction is computational and also practically expensive [26]. In particular, many researchers have claimed that reconstructing 3D surface from uncalibrated 2D images is an ill-posed problem and prone to errors [27, 28]. However, it is not impractical and still has a possibility to be improved and fill the gap by capturing image in multiple-views to cover hidden or unseen parts of an object. Thus, each 2D image is captured by a digital camera using a turntable in order to acquire sufficient information of an object by capturing more than one 2D image at different angle of projections. The idea of multiple-views or different projections of an object in the scene is a compliment to the tomographic imaging technique in order to provide corresponding information between projections.

This thesis also seeks the comprehension of the related literatures in order to understand and make contributions to the body of knowledge based on the objectives, and significance of study listed in the following sections. In fact, the component of prosthesis requires a very high customization level in order to suit both functional and comfort requirements. It is vital to measure the reconstructed 3D surface and compare with the real object since the accuracy in the measurements of the feature have to be as precise as possible. The recovery of an amputee depends on how the prosthesis is fitted since the prosthetic fitting affects the degree of comfortability, energy expenditure and utility [29], consequently the amputee can continue with his normal daily activities [5, 30]. Hence, the developed method must be analysed by reconstructing various shapes of objects to verify the capability the method used. The reconstructed 3D surface is compared with the actual model of residual limb to analyse and evaluate the relevance of the results obtained for any inaccuracy in the measurement.

1.3 Objective of Study

3D surface reconstruction is indeed an intriguing topic and currently receiving increased attention in the research field. The main purpose of this project is to develop 3D imaging algorithm that reconstructs 3D surface of an object from 2D images. The 2D images are obtained from an uncalibrated digital camera. The whole experimental configuration needs to be as simple as possible and easy to be set up in order to create a procedure with high repeatability and reproducibility test. It is also important to consider the cost of equipment and devices involved for an affordable 3D surface reconstruction system. Hence, the objectives of this thesis are as follows;

1. To reconstruct 3D surface using multiple-views from a digital camera and a turntable with the concept of tomographic imaging technique.
2. To develop a new algorithm based on Radon transform for image-based 3D reconstruction from uncalibrated 2D image sequences.
3. To test and verify the proposed method on amputated lower limb models for prosthetic design application.

1.4 Scope of Study

This thesis has developed a combination of existing methods to tackle the problems identified in prior research related to 3D reconstruction of prosthetic model from different perspective by focusing on passive method. It has positively identified from the reviews that the procedure of image-based 3D reconstruction is practically cost-effective for example as proposed in [25], data acquisition is performed in a dark room with light beam is projected on the object resulted to high contrast images. However, in case of prosthetic design, it is not suggested to deal with a patient in a dark room and it is also practically inefficient. It is also important to make sure the patient is in healthy mental condition and comfortable during the process of data

acquisition. Although this thesis only focused on reconstructing 3D surface of residual limb model, but it is important to consider and solve such problem which is also contribute to generate input image free from grain noise. Thus, in this study, 2D images are simply taken in a well-illuminated room where an object placed on a turntable which involved a simple experimental setup. The experimental objects are designed and carved as amputated lower limb which requires high reconstruction accuracy and also very challenging to reconstruct a 3D surface of such object in detail. The size of the models can be measured and compared for the consistency of the computation. The 3D surface reconstruction of residual limb model is acquired using uncalibrated digital camera fixated on a tripod stand. It is simpler and affordable compared to expensive medical imaging devices which requires an expertise in the process of handling. The camera is set to focus on the object which is placed on a manually rotated turntable in front of black colour background as an alternative to create a better contrast between the object and the background instead of performing the image acquisition in a dark room with projected light beam. Henceforth, the 3D surface of an object is reconstructed from the collected data by using tomographic reconstruction approach based on shape-from-silhouette methods supplemented with Radon transform in order to generate the 3D model layer by layer. The geometric features of reconstructed 3D surface for example, the height and the diameter are extracted and analyzed to estimate the computation errors of the developed algorithm in order to understand the factors causing the inaccuracy of the computation that set off the differences between the measurement of the real model and the reconstructed 3D surface.

1.5 Significance of Study

Developments in the technology of 3D imaging have been focused on fitting artificial limbs. The use of 3D reconstruction in prosthetic design has overcome the limitations of the plaster-casting method in traditional prosthetic socket fabrication and avoid making a positive mould by the way of manual modifications. In addition to this, it can provide a scientific basis for the individualization of prosthetic design [9]. On

the other hand, financial constraints are among the stresses that may complicate adjustment to limb loss. This project is conducted to contribute new cost-efficient system for design as well as to reduce the cost of production. Moreover, there are some potential benefits for a person with comfortably fitted prosthesis, for example [4, 31]:

1. The person is able to avoid from developing medical complications or difficulties, such as joint contractures, pressure ulcers, and orthostatic hypotension.
2. The person is able to lowers the stress on the joints of the opposite leg, which are adversely affected by both compensatory actions as well as by the forces applied during static single-limb weight bearing.
3. The person will be financially benefit society, not only in terms of restoring someone to a productive life but also because people fitted with prostheses are more likely to leave the nursing facility and return home.

1.6 Thesis Outlines

This thesis is organized and separated into five main chapters. Starting with Chapter 1 which is assigned for general introduction based on the title of this project. It consists of the project background, problem statements, objectives, scopes, significance and contributions of the study. Chapter 2 contains literature reviews and relevant theories that gives brief explanations on the process of prosthetic design and fundamental of 3D reconstruction methods established. It also explains the related approaches to the proposed method of this study. Chapter 3 concentrates on methodology regarding the experimental set up for image acquisitions and system implemented to reconstruct 3D objects from multiple views of uncalibrated 2D image sequences. Chapter 4 presents the results for the 3D surface reconstruction of amputated lower limb models attached with some analysis and discussion that provide reasoning for the results obtained. Chapter 5 conclude the findings and contributions from the study in this thesis to the society including the limitations with some recommendation for the possible future work as a continuation may arise to this study.

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