THREE DIMENSIONAL SURFACE RECONSTRUCTION OF LOWER LIMB PROSTHETIC MODEL USING INFRARED SENSOR ARRAY

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To my beloved husband and family

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ABSTRACT

This thesis addresses the development of a shape detector device using infrared sensor to reconstruct a three-dimensional image of an object. The three-dimension image is produced based on the object surface using image processing technique. Conventionally, infrared sensors are used for detection of an obstacle and distance measurement to avoid collisions. However, it is not common to use infrared sensors to measure the size of an object. Hence, this research aims to investigate the feasibility of infrared sensors in measuring the object dimension for three-dimension image reconstruction. Experiments were executed to study the minimum distance range utilising GP2D120 infrared sensor. From the experiment, the distance between the sensor and object surface should be more than 5 cm. The scanning device consists of the infrared sensor array was placed in a black box with the object in the center. The scanning process required the object to turn 360 ° clockwise in an *xy* plane and the resolution for z-axis is 2 mm, in order to obtain data for the image reconstruction. Reference polygon shape models with various dimensions were used as scanning objects in the experiments. The device scans object diameter every 2 mm in thickness, 100 mm in height, and the total time required to collect data for each layer is 60 seconds. The reconstructed object accuracy is above 80 % based on the comparison between a solid and printed model dimension. Four different lower limb prosthetic models with different shapes were used as the object in the scanning experiments. The experimental findings show that the prosthetic shapes reconstructed with an average accuracy of 97 %. This system shows good reproducibility where the collected data using the infrared sensor device need further improvement so that it can be applied in medical field for orthotics and prosthetics purpose.

ABSTRAK

Kajian ini bertujuan bagi mencipta alat pengesan bentuk menggunakan sensor inframerah bagi melakar semula tiga dimensi objek berkenaan. Permukaan tiga dimensi objek ini dihasilkan menggunakan teknik pembinaan semula imej. Kebiasaannya, sensor inframerah digunakan bagi mengesan halangan dan jarak bagi mengelakkan pelanggaran. Walau bagaimanapun, ianya jarang digunakan untuk mengukur saiz sesuatu objek. Justeru itu, kajian ini dilakukan bagi mengenal pasti kebolehupayaan sensor inframerah untuk mengukur saiz objek bagi tujuan pembinaan semula imej tiga dimensi. Eksperimen dijalankan bagi menentukan jarak terdekat dengan menggunakan sensor inframerah GP2D120. Hasil kajian menunjukkan bahawa, jarak di antara sensor inframerah dan objek haruslah melebihi 5 cm. Alat pengesanan ini terdiri daripada beberapa sensor inframerah yang diletakkan di dalam kotak hitam bersama dengan objek yang berada di tengah kotak. Proses pengesanan memerlukan objek untuk berpusing sebanyak 360 ° mengikut arah jam di paksi *xy* dan berketepatan sebanyak 2 mm bagi tujuan pembinaan semula imej. Beberapa bentuk poligon yang terdiri daripada pelbagai saiz digunakan di dalam eksperimen ini. Alat ini mengesan objek bagi setiap 2 mm ketebalan, 100 mm tinggi, dan jumlah masa yang diperlukan adalah sebanyak 60 saat bagi setiap lapisan. Ketepatan pembinaan semula objek adalah melebihi 80 % berdasarkan kepada perbezaan di antara rujukan dan data yang diperolehi. Empat bentuk model prostetik dengan bentuk yang berbeza turut digunakan di dalam ujikaji ini. Hasil kajian menunjukkan purata ketepatan imej adalah 97 %. Alat ini menunjukkan keputusan yang baik dalam pengambilan data menggunakan sensor inframerah dan penambahbaikan perlu dilakukan supaya ia boleh digunakan secara meluas didalam bidang perubatan orthotik dan prostetik.

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LIST OF ABBREVIATION

3D	-	Three-Dimension
CT-Scan	-	Computed Tomography Scan
MRI	-	Magnetic Resonance Imaging
2D	-	Two Dimension
US	-	Ultrasound
LD	-	Laser diode
PSD	-	Position Sensing Detector
IR	-	Infrared
ToF	-	Time of Reflect
CAD/CAM	-	Computer-aided Design and Computer-aided Manufacturing
FEA	-	Finite Element Analysis
ABC	-	American Board of Certification in Orthotics, Prosthetics & Pedorthics
BOC	-	Board for Orthotics/Prosthetic Certification
AIPP	-	Amputee Independent Prosthesis Properties
RE	-	Reverse Engineering
ADC	-	Analog-to-Digital Converter
LED	-	Light emitting diode
FKCN	-	Fuzzy Kohonen Clustering Network
IC	-	Integrated circuit
PWM	-	Pulse Width Modulation
USB	-	Universal Serial Bus
ICPS	-	Input Capture Programming

ABS	-	Acrylonitrile Butadiene Styrene
.txt	-	Text file
PCB	-	Printed Circuit Board

LIST OF SYMBOLS

θ	-	angle
α	-	Alpha
β	-	Beta
cm	-	centimeter
°	-	degree
C_o	-	Diffusivity
D	-	distance
GND	-	ground
Hz	-	Heartz
V_{in}	-	Input Voltage
kPa	-	kilo Pascal
I	-	Light Intensity
μ_s	-	Light Source
MHz	-	Mega Heartz
μF	-	micro Farad
mm	-	millimeter
ms	-	milliseconds
%	-	percent
π	-	phi
η	-	Power of Specular Reflected Light
R	-	radius
V_{ref}	-	Reference Voltage
μ_r	-	Reflected

s	-	seconds
C_1	-	Specularity
$\Delta\theta$	-	Step Size
μ_n	-	Surface Normal
μ_v	-	Viewing Vector
V_{cc}	-	Voltage

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CHAPTER 1

INTRODUCTION

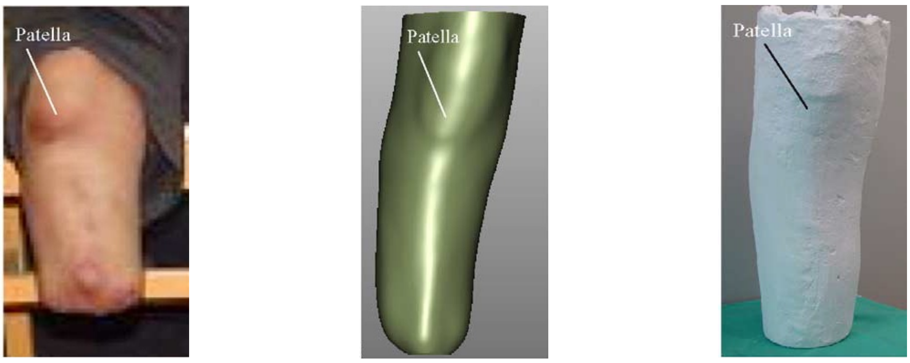
1.1 Background

A three dimension (3D) image obtained from Computer Tomography (CT) Scan, and Magnetic Resonance Imaging (MRI) are crucial in order to assist medical diagnosis and analysis. These medical data provide good results but with high cost. Meanwhile, by using two dimension (2D) images, several simulations can be done for the needs of the user. However, a proper experiment analysis is required to correct the obtained results that will cause additional cost for the test [1]. A 3D image is very important as it gives full imaging details of the measured object which will allow efficient evaluation.

A 3D image gives more data compared to 2D data images. Therefore, providing 3D images for biomedical measurement is always better than having only 2D images to analyse patients' conditions and their needs. Reconstructing a 3D image requires the use of a sensor array that is normally consisted of more than one sensor. A solution needs to be identified in order to reduce the number of sensors used to obtain data in the 3D image. It will give an advantage to medical practitioners by providing them with 3D data image, especially in orthotic and prosthetic departments. Lower limb prosthetic, for example, requires detailed information of a patient's limb condition before designing a suitable and comfortable prosthetic limb for the patient. Figure 1.1 shows an example of a lower limb prosthetic model design.

Figure 1.1 Lower limb prosthetic model design

Conventionally, medical practitioners use chalk bandages to make new design of prosthetic limb for their patients. Compared to other disability designs, prosthetic is the most challenging research in order to properly interface between the device and human body part to make sure that it fits and comfortable to the user [2]. Prosthetic is defined as a medical field in substituting or a replacement of a missing limbs with an artificial substitution [3]. Basically, to reconstruct a residual limb, a Prosthetic Technician needs to know the step from taking data to the reconstruction of the image until the limb design is completed. This 3D reconstruction offers many advantages, as the 3D image depends on the software and computer analysis to produce more accurate data [4]. Figure 1.2 shows how researchers reconstructed a 3D image and finally produce a plaster mould of a residual limb.



(a) (b) (c)

Figure 1.2 (a) The prosthetic lower limb, (b) the 3D model image of the amputee's skin, and (c) a plaster casting mould of the patient produce from the 3D model image

Figure 1.2 shows the step by step reconstruction of the plaster mould based on the prosthetic limb. In order to create the plaster based on the prosthetic limb, a 3D skin model is needed, and it is generated using various types of sensors. These sensors are used and installed in the device to capture data for reconstructing the images using the prosthetic lower limb.

Laser scanner, ultrasound (US), laser diode (LD), position sensing detector (PSD), camera and infrared (IR) are used to reconstruct a 3D image of an object. The sensor had its own advantages and drawbacks. The comparison between each device can be seen based on their accuracy, resolution, cost, and time to collect data. IR sensor has proven to be able to measure distance, and the data collected is used to reconstruct an object's surface.

Over the years, there have been significant improvements in the mobile robot technology field as well as in devices implemented with infrared sensors. Infrared sensor is one of the commonly used sensors in mobile robots. The sensor has many applications such as to measure distance [5], avoidance system [6], and also obstacle detection [7]. Other than that, it offers low price, easy installation, portable, and provides a fast response.

IR sensors have been widely used in mobile robots with several functions, and some of the researcher combines IR with other sensors to improve the results obtained. For example, IR with the 3D camera to increase the resolution of the image, IR combined with ultrasound helps in creating 3D images of an object [8], and IR installed with 3D depth sensor can be used to measure the depth and distance of an object [9].

1.2 Problem Statement

With the advancement of technology, there are a lot of devices that can be used to reconstruct the 3D image from model surfaces. Some devices offer very accurate data but with high cost, faster data preview but in 2D form, higher resolution image but require a very high computational system, and also wide sensing area but low in resolution. All the devices have their own advantages and disadvantages. Infrared sensors offer low cost, small size, portable, lightweight and require a few components in order to operate.

The problems with devices that are installed with infrared sensor in the system are that they are highly dependent on object reflectance [10]. Transmitted signal from the sensor is reflected when it hits the boundary of the reflected beam or from the intensity of the reflected light [11]. The object surface is very important in collecting a high impact of reflected signal to the sensor. If the object surface is too rough, the transmitted signal is unable to highly reflect to the sensor receiver. Small number of IR sensors installed in the device [15] will take more time to collect data in a certain active area. Each sensor has their time of reflect (ToF) measured, which will give results or data to the device [10]. With a small amount of IR sensors used, total time required to obtain the data is longer.

In Orthotic and Prosthetic department, the development of lower limb prosthetic socket required an expertise to reconstruct the shape of the residual limb that takes a long time to complete the socket [12]. Some of the hospital used advance technologies to reconstruct the 3D image of a residual limb. MRI and CT-Scan have been used, and it requires patient to lie down at the bed that will deform the actual shape of the limb [14, 15, 16]. Radiation from the CT-Scan will give a negative effect to the patient [33, 34]. Other than that, the cost is too high and not everybody can afford to use the technology. Traditional method to reconstruct the residual limb is by using plaster casting. Problem occurred when the cast is dry it will shrink, and the actual size of the socket is change. Patient will not be comfortable with the socket that could cause skin irritation, tissue damage and ulcer to the skin [2, 20].

1.3 Research Objectives

Based on the problem statement, there are three objectives in the research to be achieved. All the objectives are listed below:

a. To design a system that is capable to control the function of an infrared sensor array for prosthetic model data collection.

b. To develop an Arduino Microcontroller algorithm to control infrared array sensor data acquisition and image reconstruction algorithm using Matlab.

c. To analyse and evaluate the system performance based on the measured results and the reconstructed images.

1.4 Scope of the Thesis

The scope of this research is divided into two different parts, which is designing the device to collect data for a lower limb prosthetic model and post-processing the information on the data analysis algorithm to reconstruct the 3D image. Details of each scope are explained as follows:

a. Designing and implementing a controller circuit using Arduino microcontroller for infrared array sensor and to rotate the prosthetic model. Five infrared sensors are installed in the device with a control board that is responsible to monitor the function of the overall system. Arduino is used as a microcontroller in the device to harvest data from the IR sensors and controls the rotation of the stepper motor. It also controls the switches of the sensor since it will only turn ON one at a time to avoid any redundant reflectance signal from other IRs.

b. Integrating the system with an actuator motor which is able to slowly bring up the model to the sensor array to collect data for the whole body. An object is placed at the center underneath the IR sensor array, and the data is collected for image reconstruction purposes. In order to increase the height of an object, a cupboard with a thickness of 2 mm has been slotted underneath the object so that the device is able to measure data for the whole object.

1.5 Significant Findings

This section describes the contribution of the research works in the field of a 3D image reconstruction for a lower limb prosthetic. Experimental investigation of the development of the device is presented in this thesis. The major outcomes of this thesis can be summarised as follows:

(1) To address the use of IRs installed in the device, an experimental investigation was conducted on the principal sensor to measure the distance of an object without any support from other sensors. Researchers added other sensors in the device in order to obtain more accurate data for the results that also required a correct arrangement between the sensors to avoid any redundant signals.

(2) The IR sensor has been used widely in measuring distance, avoid collision and to detect any obstacles located in front the device. The application of IR to reconstruct the 3D image of a lower-limb prosthetic design has not yet been reported. Data from the sensor could be used to reconstruct the prosthetic lower limb with an accurate measurement. The accuracy is calculated based on the diameter of the prosthetic model itself.

(3) A device installed with IR sensors to collect data of a prosthetic model was introduced. Experimental investigation was conducted to the device, and the results were used in the image reconstruction.

1.6 Thesis Overview

A review of a lower limb prosthetic socket development with the present study is given in Chapter 2, including the application of IR sensors in measuring the distance of an object's surface. Then, in Chapter 3, the conceptual design of a shape detector device is illustrated with the experimental investigation on the infrared sensor characteristics, working principle of the control board design, sensor array model, and the hardware device of the system. Meanwhile, Chapter 4 described the shape detector device tested with various shapes of polygon models, detailed explanation on the size of the polygon model used in the experiment, equation used to convert the sensor value to the distance in a centimeter (*cm*), and the results of the 3D image reconstruction of the polygon shape are also shown. The repeatability results of the object are discussed, and the accuracy proved the effectiveness of the device. Next, the application on the lower limb prosthetic socket is tested in Chapter 5. Details on the prosthetic model used in the experiment are explained, image analysis of the prosthetic with the percentage of accuracy is also shown. The same concept is applied to a chicken drumstick to measure the accuracy of the device. Finally, the thesis concludes in Chapter 6 with an outlook on future project development.

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