UNIVERSITI PUTRA MALAYSIA

DEPTH VALUE APPROXIMATION OF 2D COMPLEX-SHAPED OBJECTS FOR 3D MODELLING USING OPTICAL FLOW AND TRIGONOMETRY

NG SENG BENG

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By

NG SENG BENG

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

January 2015

DEDICATION

This work is dedicated to all my family members who had given me support towards the completion of this thesis.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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January 2015

Chairman: Associate Professor Lili Nurliyana Abdullah, PhD
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Three dimensional (3D) modelling of physical objects can be very useful in many areas, such as computer graphics and animation, robot vision, reverse engineering, and medical. 3D modelling can be done from the scratch using modelling software, or digitised from real world objects. The process of modelling with software often consumes much time and requires a steep learning curve. On the other hand, conventional digitisation methods utilise Coordinate Measuring Machines (CMMs) or laser scanners. Nevertheless, both of these devices are very costly and require a certain amount of technical knowledge during usage and maintenance. An alternative approach which sacrifices some accuracy to greatly reduce the implementation costs will be Image-Based Modelling (IBM).

This research introduces an IBM technique using optical flow and trigonometry with images captured via webcams. The implementation cost is reduced as it only requires a laptop, a webcam and a simple experiment setup. Image pairs with known small angle rotations and distance from the camera are the required inputs.

Feature points were detected using good features to track and the displacement magnitudes were obtained via pyramidal implementation of Lucas Kanade Optical Flow. Optical flow magnitudes were then related with trigonometry to deduct the depth values of the feature points. The solution was able to combine feature points from all sides to produce a set of 3D surface points. Colour information of the feature points can be extracted as well. Data enhancement algorithms were implemented to perform noise filtering and inverse perspective mapping (IPM).

Experiments were carried out with eight small complex shaped objects placed 300 mm away from the webcam. On average, the processing capacity for the solution was 1519 points per second. The average error on the approximated width dimension was 3.27% of the actual width while the average error on the depth dimension was 6.88% of the actual depth. The solution may work with as few as four images to generate a full set of 3D surface points. Future research may work

on using the detected 3D point cloud as control points for texture coordinates to produce a fully texture mapped 3D model.

Abstrak tesis ini dikemukakan kepada Senat Universiti Putra Malaysia bagi memenuhi keperluan untuk ijazah Doktor Falsafah

PENGANGGARAN NILAI KEDALAMAN OBJEK KOMPLEKS 2D UNTUK PEMODELAN 3D MENGGUNAKAN ALIRAN OPTIK DAN TRIGONOMETRI

Oleh

NG SENG BENG

Januari 2015

Pengerusi: Profesor Madya Lili Nurliyana Abdullah, PhD
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Pemodelan tiga dimensi (3D) objek fizikal boleh dimanfaatkan dalam banyak bidang, antaranya termasuklah grafik komputer dan animasi, penglihatan komputer, kejuruteraan undur dan perubatan. Pemodelan 3D boleh dilakukan dari asas menggunakan perisian pemodelan atau mendigitasikan objek dunia sebenar. Proses pemodelan dengan perisian biasanya memerlukan masa yang panjang dengan proses pembelajaran yang sukar. Kaedah konvensional pendigitan menggunakan Mesin Pengukur Koordinat (CMM) atau pengimbas laser. Namun, kedua-dua peranti ini sangat mahal dan memerlukan pengetahuan teknikal semasa penggunaan dan penyelenggaraan. Kaedah alternatif yang mengorbankan sedikit kejituan untuk mengurangkan kos pelaksanaan ialah melalui Pemodelan Berasaskan Imej (IBM).

Penyelidikan ini memperkenalkan suatu teknik IBM yang menggunakan aliran optik dan trigonometri pada imej yang diperolehi daripada kamera web. Kos implementasi adalah rendah kerana ia hanya memerlukan satu komputer riba, satu kamera web dan satu persekitaran eksperimen yang ringkas. Input yang diperlukan adalah pasangan imej dengan sudut putaran dan jarak dari kamera yang diketahui.

Titik ciri dikesan dengan *good features to track* dan magnitud sesaran diperolehi dengan menggunakan aliran optik Lucas Kanade secara piramid. Selepas itu, trigonometri digunakan untuk mengaitkan magnitud aliran optik dan seterusnya nilai kedalaman bagi titik ciri dianggarkan. Penyelesaian ini dapat menggabungkan titik ciri dari semua sisi untuk mendapatkan satu set titik permukaan 3D yang lengkap. Maklumat warna titik ciri ini juga dapat diekstrak. Algoritma penambahbaikan data digunakan sebagai penapis hingar dan Pemetaan Berbalik Perspektif (IPM).

Eksperimen telah dikendalikan dengan lapan objek kecil dan kompleks yang diletakkan 300 mm dari kamera web. Min kapasiti pemprosesan penyelesaian adalah 1519 titik sesaat dan secara purata, ralat dimensi kelebaran yang

dianggarkan adalah 3.27% daripada kelebaran sebenar manakala ralat dimensi kedalaman yang dianggarkan adalah 6.88% daripada kedalaman sebenar. Penyelesaian ini dapat berfungsi dengan hanya sebanyak empat imej untuk menjana satu set penuh titik permukaan 3D. Penyelidikan masa hadapan boleh menggunakan titik permukaan 3D ini sebagai titik kawalan bagi koordinat tekstur supaya model 3D dengan pemetaan tekstur penuh dapat dijanakan.

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I certify that a Thesis Examination Committee has met on 29 January 2015 to conduct the final examination of Ng Seng Beng on his thesis entitled " Depth Value Approximation of 2D Complex Shaped Objects for 3D Modelling Using Optical Flow and Trigonometry" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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I hereby confirm that:

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This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
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LIST OF ABBREVIATIONS

2D	Two Dimensional
3D	Three Dimensional
AR	Augmented Reality
BGR	Blue, Green, Red
CAD/CAM	Computer-Aided Design/Computer-Aided Manufacturing
CCD	Charged Coupled Device
CG	Computer Graphics
COP	Centre of Projection
COR	Centre of Rotation
CMM	Coordinate Measuring Machine
EXIF	EXchangeable Image File
FoV	Field of View
GB	GigaByte
GPU	Graphic Processing Unit
IBM	Image Based Modelling
IPM	Inverse Perspective Mapping
LK	Lucas-Kanade
MP	MegaPixels
OpenCV	Open source Computer Vision library
OpenGL	Open source Graphic Library
Pyramidal LK	Pyramidal implementation of Lucas Kanade optical flow
RAM	Random Access Memory
RGB	Red, Green and Blue
SDK	Software Development Kit
ToF	Time-of-Flight
VR	Virtual Reality

CHAPTER 1

INTRODUCTION

1.1 Overview

Real world objects are represented in computers via three dimensional (3D) digital models. The basic information required for this representation is the *x*, *y* and *z* coordinates. Further manipulation of these coordinates can deduct the objects' dimensions (width, height and depth). Other attributes such as the models' surface colour, texture, lighting, shading and shadow can contribute to a more realistic representation.

Digital 3D models can be created from the scratch or using predefined templates in 3D modelling software. These models usually are fictional and artistic or newly designed models which have not been manufactured yet. The 3D artists are unable to get hold of the real physical objects or these objects which are not available in the real world yet and hence give them no choice but to model from scratch. Examples of 3D models that are created using modelling software include robots and monsters for movies and games, prototype design models which are to be sent for manufacturing and virtual environments which cannot be digitised accurately or visually realistic via any other methods.

For models that are based from real objects, high cost gadgets or machines such as the Coordinate Measuring Machine (CMM) or laser scanner can be used to digitise these physical objects. Both CMM and laser scanner are expensive and require some technical knowledge to operate them. CMM requires a large space to accommodate the big machine and a relatively long processing time in exchange for accuracy. Meanwhile, the laser scanner processes faster, but sacrifices some accuracy. Laser scanner also has problems on objects with shiny surfaces or objects that do not reflect light, which include black colour and transparent surfaces.

Conventional imaging techniques record the real world scene into a two dimensional (2D) image or video, using a camera or a video recorder respectively. These recording techniques are affected by the perspective projection effects and also suffer the loss of the depth (*z* axis) information. Image Based Modelling (IBM) techniques try to tackle the reconstruction problems with single or more images. These techniques will be discussed in Section 2.3.

1.2 Problem Statement

Conventional 3D modelling methods are constructed either through developing from the scratch using 3D modelling software or obtaining the 3D surface points from physical objects using the CMMs or the laser scanners. Nevertheless, these methods require certain amount of technical knowledge or experience, either to use the software or to operate the machines. In addition, CMMs and laser scanners are very costly. Generally CMM is only able to obtain the profile and surface of an object as sample points, while most laser scanners are able to obtain the 3D model, both without colour information. Some high-end laser scanners captures high resolution images to be mapped on the 3D model produced by the laser scanner, but an issue of accurate alignment between the geometry and colour can occur (Koutsoudis, Vidmar, & Arnaoutoglou, 2013). Laser scanners are also vulnerable to highly specular surfaces, concave surface regions and materials affected by subsurface scattering.

IBM has been an alternative to produce 3D models using image processing techniques with a much lower hardware cost (Tong, Zhou, Liu, Pan, & Yan, 2012; Azevedo, Tavares, & Vaz, 2009; Remondino & El-Hakim, 2006). Other than that, IBM can be applied on large objects that cannot fit into the scanning area or distance of laser scanners or CMM. In another case, small objects that requires high scanning resolution also cause an issue on the conventional scanning methods. IBM does not have the issue of unable to process huge or tiny objects, as long as those objects can be captured into image(s) or video(s) to be processed with computers. This can be easily done by changing the camera (or lens) to capture detailed images, without being bounded by the range and environment interference limitations in active sensors such as those using laser or infrared.

Nevertheless there are still room for research in terms of generated 3D model's accuracy, algorithm complexity, hardware requirements, and also environment setup and space needed. Since the release of Microsoft Kinect in 2010, which is a depth sensor of a much lower cost, researches in IBM had gained some momentum.

Many recent IBM researches have been using Microsoft Kinect as a 3D sensor because the implementation costs are relatively low and the results produced are satisfactory. Nevertheless, there still are some limitations within that depth sensor. Since it uses infrared, the sensor is not suitable to be used outdoors where the ambient light is too bright (Room lighting conditions for Kinect, n.d.; Riyad A. El-laithy, 2012). In addition, with the pseudorandom pattern projected and depth value being estimated using stereo triangulation technique, the effective working range is claimed to be within 40 centimetres and 5 metres. And hence, small objects cannot be focused closely and large and far objects cannot be captured in detail.

All in all, conventional scanning methods with CMM and laser scanners are too costly in terms of hardware price and the requirement for expertise to operate. Although the recently release Microsoft Kinect seems to be more economical to operate and implement IBM, it still has its limitations due to the hardware design that is initially not being dedicated for 3D modelling.

An alternative IBM technique must be introduced that can be of low implementation cost in terms of hardware requirements and expenses, and ease of use which does not have the restrictions as in depth cameras. In addition IBM techniques has minimum dependency on hardware specifications, and hence has a better potential to be widely implemented and used by the public, maybe on mobile devices too.

1.3 Research Objectives

With reference to the above mentioned problems, an alternative IBM algorithm is proposed. This IBM is targeted to achieve the following objectives:

- to propose an equation for depth value approximation of 2D feature points using optical flow and trigonometry, hence reducing the hardware dependency in depth value approximation techniques.
- to propose a low complexity IBM technique that extracts feature points from images of small complex shaped objects from different views and merge into a set of 3D surface points with colour information.
- to design and implement an algorithm with a set of noise filtering techniques that is able to remove noise detected from input images and outliers generated in 3D model with an optimum dimension.

1.4 Research Contributions

This research is aimed to have the following contributions:

- Propose an algorithm that utilizes optical flow and trigonometry for depth value approximation from 2D images. Since the proposed technique uses passive optical input device (webcam or digital camera), it will not be restricted by the emitter's limitation of range (infrared in Microsoft Kinect or laser beam in laser scanner).
- Merging of individual surface points from different views and deducting a hybrid inverse perspective mapping (IPM) to eliminate the distortion caused by perspective projection on the feature points extracted from the images. A set of 3D surface points of the whole small complex shaped objects is generated by merging individual 3D surface points from several different views. The whole 3D model of small complex shaped object in actual dimensions is produced by implementing image coordinate to world coordinate conversion. The surface points have colour information obtained from the input images.
- An algorithm with steps of noise filtering and generate a clean set of 3D cloud of surface points.

1.5 Scope

This research is limited to the following scope:

- Images for the input of the solution must be taken on a specific environment setup, which will be described in Section 3.3.1.
- The filtering techniques used are to remove wrongly matched feature points in optical flow and outliers in approximated depth value. They do not include subject detection and segmentation from a noisy background.

- Subjects of which images will be taken for the depth value estimation process must be rigid (does not deform from time to time), has features such as colours, textures and patterns on the surface to be detected, and not highly reflective or shiny. Parts that have the same colour as the setup's background cannot be detected. Subjects that have features changing over time or from different viewing angles are not suitable for the solution. Examples of such subjects are digital display devices showing movie clips during image acquisition or mirrors that reflects other features that does not belong to the subject.
- Pyramidal implementation of Lucas Kanade optical flow (Pyramidal LK) is used in the implementation of the solution to show the ability of optical flow to be used in IBM. Its performance and signal to noise ratio is not to be studied.
- This research does not include surface patching for subjects with hidden or occluded surfaces.
- This research is to detect features from colour images to estimate their depth values. The 3D surface points generated are to be visually similar to the original object with acceptable accuracy.
- The solution was tested on eight randomly selected table top objects which exhibit different visual appearance.
- Current solution only merges up to six views (twelve input images).

1.6 Structure of Thesis Organisation

This thesis consists of seven main chapters, as summarised in Figure 1.1. Boxes in green represent the study of the experiment procedure and various variables involved in the solution while boxes in orange are the sections with experiments conducted to analyse the outcome of the solution. As for the boxes in pink, they represent sections where further experiments were conducted to study the performance of the solution, in terms of the reduction of number of image sets used and with different small rotational angles.

The first chapter introduces some background information about 3D modelling techniques and point out the problems that exist in current technology. Research objectives, contributions and scope will be specified there. The second chapter introduces the current physical objects digitisation techniques and IBM techniques. This is followed by some reviews regarding Microsoft Kinect, which appears to be the currently popular device for digitising physical objects. Next, optical flow which is used in the solution's tracking process. Some recent researches in IBM is summarised in this chapter too.

The third chapter of this thesis shows the methodology and research framework in detail. This chapter also explained the experiments setup and some preliminary experiments conducted to determine the optimal parameters for the solution.

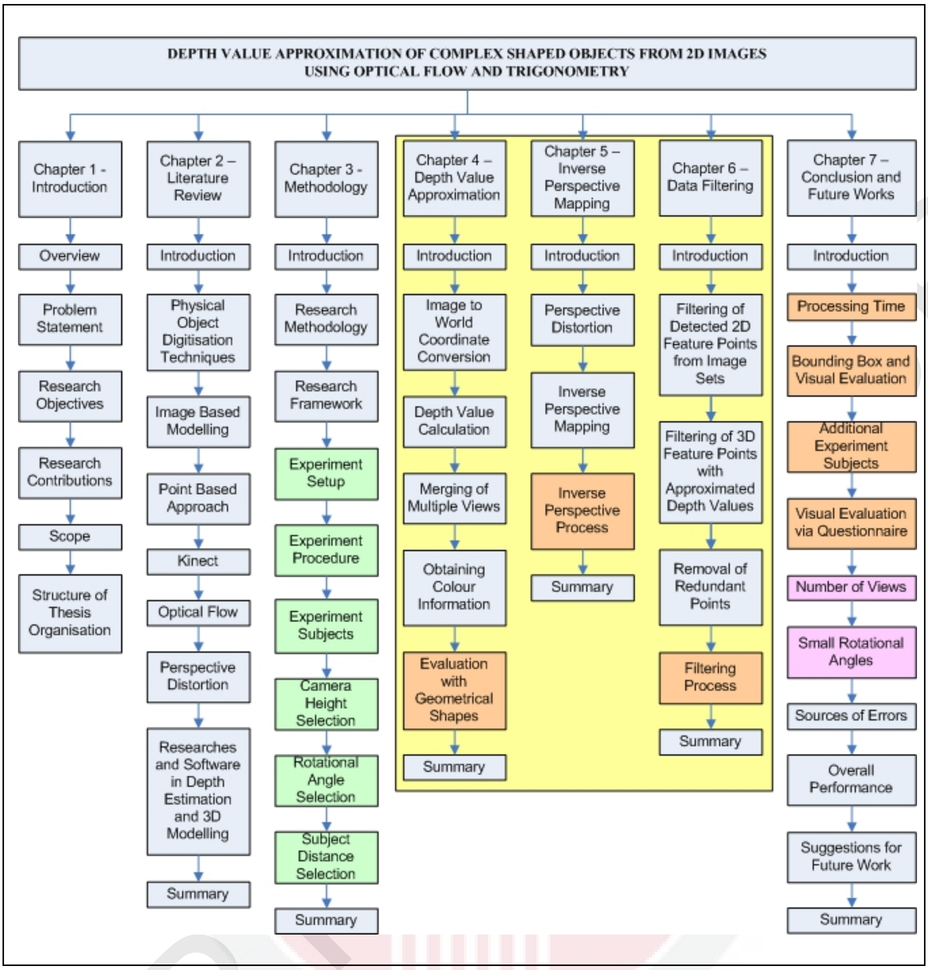

Figure 1.1: Thesis Organisation

The yellow box framing Chapters four, five and six in Figure 1.1 indicates that these chapters are the research contributions. Chapter four will explain the implemented depth approximation technique, including the image-to-actual dimensions scaling process, the deducing of the formula, the merging of multiple views and the colour information extraction process. Evaluation of the solution was done on geometrical shapes.

Chapter five details the causes of perspective distortion and the Inverse Perspective Mapping (IPM) processes used to correct it. Meanwhile, Chapter six will explain on the filters used which include 2D and 3D noise filtering techniques, and redundant points removal steps.

The seventh chapter will present the evaluations conducted upon the solution and their discussions. The solution was examined in terms of processing time, bounding box and visual evaluation. The solution was implemented on more experiment subjects were to test its robustness. Results of questionnaire with experts will also be discussed in this chapter. Finally, sources of errors and some potential future works for this research are also pointed out.

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