



**UNIVERSITI PUTRA MALAYSIA**

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

**NG SENG BENG**

**FSKTM 2015 21**



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

**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**

## **COPYRIGHT**

All material contained within the thesis, including without limitation text, logos, icons, photographs and all other artwork, is copyright material of Universiti Putra Malaysia unless otherwise stated. Use may be made of any material contained within the thesis for non-commercial purposes from the copyright holder. Commercial use of material may only be made with the express, prior, written permission of Universiti Putra Malaysia.

Copyright © Universiti Putra Malaysia



## **DEDICATION**

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





© COPYRIGHT UPM

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

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

By

**NG SENG BENG**

**January 2015**

**Chairman: Associate Professor Lili Nurliyana Abdullah, PhD  
Faculty: Computer Science and Information Technology**

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  
MENGUNAKAN ALIRAN OPTIK DAN TRIGONOMETRI**

Oleh

**NG SENG BENG**

**Januari 2015**

**Pengerusi: Profesor Madya Lili Nurliyana Abdullah, PhD**  
**Fakulti: Sains Komputer dan Teknologi Maklumat**

Pemodelan tiga dimensi (3D) objek fizikal boleh dimanfaatkan dalam banyak bidang, antaranya termasuklah grafik komputer dan animasi, penglihatan komputer, kejuruteraan undur dan perubahan. 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 pengidatan 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 kejutuan 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 pemrosesan 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.



## ACKNOWLEDGEMENTS

A special thanks to my main supervisor, Associate Professor Dr. Lili Nurliyana Abdullah, co-supervisors, Associate Professor Dr. Rahmita Wirza O.K. Rahmat, Associate Professor Dr. Fatimah Khalid and Associate Professor Dr. Oteh Maskon for their advice and support that led me throughout the research and thesis writing process.

And also I would like to express my gratitude to my family members, namely my mum, my wife and my brother that gave me moral support and motivation which helped me get through the hard times.

Last but not least, I would like to thank all lecturers and support staffs from the Faculty of Computer Science and Information Technology that have given me help directly or indirectly towards the completion this thesis.

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.

Members of the Thesis Examination Committee were as follows:

**Mohamed Othman, PhD**

Professor  
Faculty of Science Computer and Information Technology  
Universiti Putra Malaysia  
(Chairman)

**Shyamala Doraisamy, PhD**

Associate Professor  
Faculty of Science Computer and Information Technology  
Universiti Putra Malaysia  
(Internal Examiner)

**M. Iqbal bin Saripan, PhD**

Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Internal Examiner)

**Mubarak Shah, PhD**

Professor  
Center for Research in Computer Vision  
University of Central Florida  
United States  
(External Examiner)

---

**ZULKARNAIN ZAINAL, PhD**

Professor and Deputy Dean  
School of Graduate Studies  
Universiti Putra Malaysia

Date: 12 August 2015

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

**Lili Nurliyana Abdullah, PhD**

Associate Professor  
Faculty of Science Computer and Information Technology  
Universiti Putra Malaysia  
(Chairman)

**Rahmita Wirza O.K. Rahmat, PhD**

Associate Professor  
Faculty of Science Computer and Information Technology  
Universiti Putra Malaysia  
(Member)

**Fatimah Khalid, PhD**

Associate Professor  
Faculty of Science Computer and Information Technology  
Universiti Putra Malaysia  
(Member)

**Oteh Maskon, PhD**

Associate Professor  
Cardiologist  
Universiti Kebangsaan Malaysia Hospital  
(Member)

---

**BUJANG KIM HUAT, PhD**

Professor and Dean  
School of Graduate Studies  
Universiti Putra Malaysia

Date:

## Declaration by Graduate Student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any other institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and Innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software.

Signature: \_\_\_\_\_ Date: \_\_\_\_\_

Name and Matric No.: Ng Seng Beng (GS21626)

## Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

Signature: \_\_\_\_\_  
Name of Chairman of  
Supervisory Committee: Lili Nurliyana Abdullah

Signature: \_\_\_\_\_  
Name of Member of  
Supervisory Committee: Rahmita Wirza O. K. Rahmat

Signature: \_\_\_\_\_  
Name of Member of  
Supervisory Committee: Fatimah Khalid

Signature: \_\_\_\_\_  
Name of Member of  
Supervisory Committee: Oteh Maskon

## TABLE OF CONTENTS

	<b>Page</b>
<b>ABSTRACT</b>	i
<b>ABSTRAK</b>	iii
<b>ACKNOWLEDGEMENTS</b>	v
<b>APPROVAL</b>	vi
<b>DECLARATION</b>	viii
<b>LIST OF TABLES</b>	xiii
<b>LIST OF FIGURES</b>	xvi
<b>LIST OF ABBREVIATIONS</b>	xix
<b>CHAPTER</b>	
<b>1</b>	<b>INTRODUCTION</b>
	1.1 Overview 1
	1.2 Problem Statement 1
	1.3 Research Objectives 3
	1.4 Research Contributions 3
	1.5 Scope 3
	1.6 Structure of Thesis Organisation 4
<b>2</b>	<b>LITERATURE REVIEW</b>
	2.1 Introduction 7
	2.2 Physical Objects Digitisation Techniques 8
	2.2.1 Contact Based System 9
	2.2.2 Non-contact Based Scanner 10
	2.3 Image Based Modelling (IBM) 14
	2.4 Point Based Approach 16
	2.5 Kinect 17
	2.6 Optical Flow 20
	2.7 Researches and Software in Depth Estimation and 3D Modelling 21
	2.7.1 Robot Vision 21
	2.7.2 Reverse Engineering 22
	2.7.3 Computer Graphics 23
	2.7.4 Medical 24
	2.8 Summary 24
<b>3</b>	<b>METHODOLOGY</b>
	3.1 Introduction 25
	3.2 Research Methodology 25
	3.3 Research Framework 27
	3.3.1 Image Acquisition 28
	3.3.2 Feature Tracking and Optical Flow 28
	3.3.3 Depth Value Approximation and Data Enhancement Steps 29

3.4	Experiment Setup	30
3.5	Experiment Procedure	33
3.6	Experiment Subjects	33
3.6.1	Actual Subjects Measurements	35
3.7	Camera Height Selection	36
3.8	Rotational Angle Selection	39
3.8.1	Subject 1	40
3.8.2	Subject 2	44
3.8.3	Subject 3	47
3.8.4	Subject 4	50
3.8.5	Subject 5	55
3.9	Subject Distance Selection	58
3.10	Summary	58
<b>4</b>	<b>DEPTH VALUE APPROXIMATION</b>	
4.1	Introduction	60
4.2	Image to World Coordinate Conversion	61
4.3	Depth Value Calculation	63
4.4	Merging of Multiple Views	66
4.5	Obtaining Colour Information	69
4.6	Evaluation with Geometrical Shapes	71
4.6.1	Subject 6 - Ball	72
4.6.2	Subject 7 – Can Drink	76
4.6	Summary	80
<b>5</b>	<b>INVERSE PERSPECTIVE MAPPING</b>	
5.1	Introduction	81
5.2	Perspective Distortion	81
5.3	Inverse Perspective Mapping (IPM)	82
5.4	Inverse Perspective Projection Process	83
5.5	Summary	87
<b>6</b>	<b>DATA FILTERING</b>	
6.1	Introduction	88
6.2	Filtering of Detected 2D Feature Points from Image Sets	88
6.2.1	Noise Filtering with Euclidean Distance and Colour Information	89
6.2.2	Removal of Wrongly Matched Feature Points	90
6.3	Filtering 3D Feature Points with Approximated Depth Values	91
6.4	Removal of Redundant Points	91
6.5	Filtering Process	93
6.5.1	Euclidean Distance	93
6.5.2	Colour Information	95
6.5.3	Points Cluster	95
6.6	Summary	96



<b>7</b>	<b>CONCLUSION AND FUTURE WORKS</b>	
	7.1 Introduction	97
	7.2 Processing Time	97
	7.3 Bounding Box and Visual Evaluation	101
	7.4 Experiment with Additional Subjects	106
	7.5 Visual Evaluation via Questionnaire	110
	7.6 Number of Views	114
	7.6.1 Subject 1	114
	7.6.2 Subject 3	117
	7.6.3 Subject 8	119
	7.7 Rotational Angles	121
	7.7.1 Detected Points and Processing Time	122
	7.7.2 Approximated Dimensions	123
	7.7.3 Comparison of Subject 7's Approximated Surface with Cylinder	124
	7.8 Sources of Errors	126
	7.8.1 Features to Track	126
	7.8.2 Noise	126
	7.8.3 Human Error	127
	7.8.4 Technical Error	127
	7.9 Overall Performance	128
	7.10 Suggestions for Future Work	130
	7.11 Conclusion	131
	<b>REFERENCES</b>	<b>134</b>
	<b>APPENDICES</b>	<b>141</b>
	A Detailed Readings on the Effects of Rotational Angle towards Approximated Dimensions for Subjects 1-5	141
	B Depth Value Approximation Formula Derivation	145
	C Detailed Results of Bounding Box Evaluation	149
	D Questionnaire	150
	E Questionnaire Respondents	159
	F Detailed Results of Experiments using Small Rotational Angles	161
	G Front, left, top and isometric views of the approximated 3D points	163
	<b>BIODATA OF STUDENT</b>	<b>173</b>
	<b>LIST OF PATENTS AND PUBLICATIONS</b>	<b>174</b>

## LIST OF TABLES

<b>Table</b>	<b>Page</b>
2.1 Passive Optical Sensors	15
2.2 Hardware Dependency of Point Based Approach for 3D Modelling	16
3.1 Construct, Concept and Variables	30
3.2 Pros and Cons of Rotating the Camera or the Experiment Subject	32
3.3 Subjects Numbers	33
3.4 Dimension Measurements of the Subjects	36
3.5 Subject's Total Height (pixels) Captured in the Image	39
3.6 Subjects' Orientations	39
3.7 Orientation Sets for Different Number of Views Used for Reconstruction	40
3.8 Number of Points Detected and Processing Time of Subject 1 using Different Rotational Angles	41
3.9 Tracking Ability in relative with the 3° Rotational Angle of Subject 1	41
3.10 Approximated Dimensions of Subject 1 using Different Rotational Angles	41
3.11 Number of Points Detected and Processing Time of Subject 2 using Different Rotational Angles	44
3.12 Tracking Ability in relative with the 3° Rotational Angle of Subject 2	44
3.13 Approximated Dimensions of Subject 2 using Different Rotational Angles	45
3.14 Number of Points Detected and Processing Time of Subject 3 using Different Rotational Angles	47
3.15 Tracking Ability in relative with the 3° Rotational Angle of Subject 3	48
3.16 Approximated Dimensions of Subject 3 using Different Rotational Angles	48
3.17 Number of Points Detected and Processing Time of Subject 4 using Different Rotational Angles	51
3.18 Subject 4's Tracking Ability in relative with the 3° Rotational Angle	51
3.19 Approximated Dimensions of Subject 4 using Different Rotational Angles	52
3.20 Number of Points Detected and Processing Time of Subject 5 using Different Rotational Angles	55
3.21 Subject 5's Tracking Ability in relative with the 3° Rotational Angle	56
3.22 Approximated Dimensions of Subject 5 using Different Rotational Angles	56
4.1 Input Values Required for the Depth Approximation Process	60
4.2 Experiment Results of Subject 6	72
4.3 Subject 6's Approximated Dimensions with One Image Set Compared to Actual Values	75
4.4 Experiment Results of Subject 7	76
4.5 Subject 7's Approximated Dimensions with One Image Set Compared to Actual Values	79
5.1 Approximated Height of Subject 1's Wing Tip with and without IPM	86
7.1 Computer Specifications for the Experiments	98
7.2 Processing Time	98

7.3	Scanning Speed Comparison of Solution with CMM Laser Line Scanner	100
7.4	Raw Point Cloud Output and Filtered Data Obtained from the Laser Line Scanners and the Solution	100
7.5	Difference of Approximated Dimensions with the Actual Measurement	102
7.6	Difference of Approximated Depth with the Actual Measurement of Subject 3 after Disabling Euclidean Distance Filter in Depth Dimension	105
7.7	Processing Time of Experiments with Additional Subjects	107
7.8	Difference of Approximated Dimensions in Subjects 8, 9 and 10	107
7.9	List of Questionnaire Respondents	111
7.10	Evaluation Results of the Respondents from the Academic Area	112
7.11	Evaluation Results of the Respondents with Work Experience	113
7.12	Subject 1's Approximated Dimensions using Four, Three and Two Image Sets	114
7.13	Subject 3's Approximated Dimensions using Four, Three and Two Image Sets	117
7.14	Subject 8's Approximated Dimensions using Four, Three and Two Image Sets	119
7.15	Number of Feature Points Detected and Processing Time of Subject 1 using Small Rotational Angles	122
7.16	Number of Feature Points Detected and Processing Time of Subject 7 using Small Rotational Angles	122
7.17	Number of Feature Points Detected and Processing Time of Subject 9 using Small Rotational Angles	122
7.18	Approximated Dimensions of Subject 1 using Small Rotational Angles	123
7.19	Approximated Dimensions of Subject 7 using Small Rotational Angles	123
7.20	Approximated Dimensions of Subject 9 using Small Rotational Angles	124
7.21	Subject 7's Approximated Dimensions with One Image Set Compared to Actual Values	124
7.22	Error Distribution of Subject 7	125
7.23	Performance Summary of the Solution	129
7.24	Average Distance Comparisons	130
A1	Approximated Width of Subject 1 using Different Rotational Angles	141
A2	Approximated Depth of Subject 1 using Different Rotational Angles	141
A3	Approximated Width of Subject 2 using Different Rotational Angles	141
A4	Approximated Depth of Subject 2 using Different Rotational Angles	142
A5	Approximated Width of Subject 3 using Different Rotational Angles	142
A6	Approximated Depth of Subject 3 using Different Rotational Angles	142
A7	Approximated Width of Subject 4 using Different Rotational Angles	143
A8	Approximated Depth of Subject 4 using Different Rotational Angles	143
A9	Approximated Width of Subject 5 using Different Rotational Angles	143
A10	Approximated Depth of Subject 5 using Different Rotational Angles	144
C1	Difference of Approximated Height with the Actual Measurement	149
C2	Difference of Approximated Width with the Actual Measurement	149
C3	Difference of Approximated Depth with the Actual Measurement	149
F1	Approximated Width of Subject 1 using Small Rotational Angles	161
F2	Approximated Depth of Subject 1 using Small Rotational Angles	161

F3	Approximated Width of Subject 7 using Small Rotational Angles	161
F4	Approximated Depth of Subject 7 using Small Rotational Angles	162
F5	Approximated Width of Subject 9 using Small Rotational Angles	162
F6	Approximated Depth of Subject 9 using Small Rotational Angles	162



## LIST OF FIGURES

<b>Figure</b>	<b>Page</b>
1.1 Thesis Organisation	5
2.1 Organisation of Literature Review	8
2.2 Division of 3D Reconstruction Methods	9
2.3 ACCURA CMM by Carl Zeiss	10
2.4 3D Scanner using Laser	11
2.5 3D Scanner using White Light	11
2.6 Airborne Laser Scanner	12
2.7 Indoor Laser Scanners	13
2.8 Non-contact based Systems using Light Wave Acquisition Methods	15
2.9 Kinect	17
2.10 Schematic View of Kinect	17
2.11 Pseudorandom Pattern Projected by the Kinect's Infrared Projector	18
2.12 Kinect's Infrared Projected Pattern and Sub-pattern Enhanced using Photoshop	19
2.13 Coded Target for PhotoModeler	22
3.1 Research Steps	26
3.2 Research Framework	27
3.3 Sketch of Experiment Setup	28
3.4 Processing Steps Involved in Depth Approximation	29
3.5 Photo of Designated Experiment Setup for Capturing Images	31
3.6 Experiment Subjects	34
3.7 Measuring Subject's Dimensions	35
3.8 Webcam Lens Height at 55 mm and the Image Taken	37
3.9 Image Taken with Webcam Lens Height at 110 mm	37
3.10 Image Taken with Webcam Lens Height at 110 mm, Tilted Downwards	38
3.11 Subject Levelled by 25.82 mm	38
3.12 0° Image of Subject 1	40
3.13 Optical Flow of Subject 1 with 3° and 35° Rotational Angles	42
3.14 Generated 3D Point Cloud of subject 1 with 3° Rotational Angle	43
3.15 Generated 3D Point Cloud of Subject 1 with 35° Rotational Angle	43
3.16 0° Image of Subject 2	44
3.17 Optical Flow of Subject 2 with 3° and 35° Rotational Angles	45
3.18 Generated 3D Point Cloud of Subject 2 with 3° Rotational Angle	46
3.19 Generated 3D Point Cloud of Subject 2 with 35° Rotational Angle	46
3.20 0° Image of Subject 3	47
3.21 Optical Flow of Subject 3 with 3° and 35° Rotational Angles	49
3.22 Generated 3D Point Cloud of Subject 3 with 3° Rotational Angle	49
3.23 Generated 3D Point Cloud of Subject 3 with 35° Rotational Angle	50
3.24 0° Image of Subject 4	51
3.25 Subject 4's Generated 3D Points with 35° Rotational Angle	52
3.26 Optical Flow of Subject 4 with 3° and 35° Rotational Angles	53
3.27 Generated 3D Point Cloud of Subject 4 with 3° Rotational Angle	54
3.28 Generated 3D Point Cloud of Subject 4 with 35° Rotational Angle	54
3.29 0° Image of Subject 5	55
3.30 Optical Flow of Subject 5 with 3° and 35° Rotational Angles	57

3.31	Generated 3D Point Cloud of Subject 5 with 3° Rotational Angle	57
3.32	Generated 3D Point Cloud of Subject 5 with 35° Rotational Angle	58
4.1	Different Subject Width with Different Orientations	62
4.2	Reduction on Effects of Self-casted Shadow	63
4.3	Sketch of the Experiment Setup from Left View	63
4.4	Sketch of the Experiment Setup from Top View	64
4.5	Translated Projection Plane	66
4.6	Approximated 3D Surface Points without Proper Merging Process	67
4.7	0° View before Merging	67
4.8	120° View before Merging	67
4.9	240° View before merging	67
4.10	3D Points with Proper Merging Step of the 0° and 120° Point Sets	68
4.11	3D Points with Proper Merging Step of All 0°, 120° and 240° Point Sets	68
4.12	Row and Column Indexes of an Image	70
4.13	Example of a 5×5 Image Representation in Two and Single Dimensional Index	71
4.14	Self-casted Shadow on the Bottom Hemisphere of Subject 6	73
4.15	Effect of Self-casted Shadow on Subject 6 Reduced	73
4.16	Approximated 3D Feature Points of Subject 6	74
4.17	Detected Feature Points of Subject 6 being Superimposed on Image	75
4.18	Subject 6's Approximated Surface Points on a Sphere Generated using Mathematical Formula	76
4.19	Feature Points of Subject 7	77
4.20	Detected Feature Points of Subject 7 being Superimposed on Image	78
4.21	Subject 7's Approximated Surface Points on a Cylinder Generated using Mathematical Formula	79
5.1	Sides of a Parallel Railroad Looked Focused	81
5.2	Formation of Perspective Projection	82
5.3	Inverse Perspective Mapping	82
5.4	Perspective Projection Effects on the Image of Subject 1	84
5.5	0° Image and Generated 3D Points	85
5.6	120° Image and Generated 3D Points	85
5.7	Initial 0° and Rotated 120° Approximated 3D Points	86
5.8	Initial 0° and Rotated 120° Approximated 3D Points After IPM	86
6.1	Black Matte Background Consisted of Textures and Shades of Grey	88
6.2	Probability Distribution of Noise	89
6.3	Region where Feature Points Cannot have their Pairs after Rotation	90
6.4	Noise Prone Region to be Filtered off	91
6.5	Pseudocode for Redundant Points Removal	92
6.6	Detected 2D Feature Points of the Glass with and without Euclidean Distance Filter	94
6.7	Top view of the Glass with and without Euclidean Distance Filter on the 3D Points	94
6.8	Euclidean Distance Filter with and without Considering Colour Information	95
6.9	Top View of the Glass with and without Filter based on Points Cluster	96
7.1	Processing Time based on Detected Feature Points	99
7.2	Subject 1's Full Coloured Surface Points and Front Converted Red Surface Points from the Left View	101

7.3	Detected Feature Points of Subject 2 being Superimposed on Image	102
7.4	Detected Feature Points of Subject 4 being Superimposed on Image	103
7.5	Detected Feature Points of Subject 1 being Superimposed on Image	103
7.6	Detected Feature Points of Subject 5 being Superimposed on Image	104
7.7	Detected Feature Points of Subject 3 being Superimposed on Image	105
7.8	Detected Feature Points of Subject 3 being Superimposed on Image after Disabling Euclidean Distance Filter in Depth Dimension	105
7.9	Additional Subjects	106
7.10	3D Point Cloud of Subject 8	108
7.11	3D Point Cloud of Subject 9	108
7.12	3D Point Cloud of Subject 10	109
7.13	Approximated 3D Point Cloud of Subject 10 using One Image Set	110
7.14	Stacked Bar Graph of Likert Scale Ratings based on Experiment Subjects, from Respondents in Academic Area	112
7.15	Stacked Bar Graph of Likert Scale Ratings based on Experiment Subjects, from Respondents with Work Experience	113
7.16	Generated 3D Point Cloud of Subject 1 using Four Image Sets	115
7.17	Generated 3D Point Cloud of Subject 1 using Three Image Sets	115
7.18	Generated 3D Point Cloud of Subject 1 using Two Image Sets	116
7.19	Self-occlusion on the Subject	117
7.20	Generated 3D Point Cloud of Subject 3 using Four Image Sets	118
7.21	Generated 3D Surface Points of Subject 3 using Three Image Sets	118
7.22	Generated 3D Surface Points of Subject 3 using Two Image Sets	119
7.23	Generated 3D Point Cloud of Subject 8 using Four Image Sets	120
7.24	Generated 3D Point Cloud of Subject 8 using Three Image Sets	120
7.25	Generated 3D Point Cloud of Subject 8 using Two Image Sets	121
7.26	Bad Features to Track with Multiple Matching Sub Patterns	126
7.27	Inconsistent Dimensions Detected	127
7.28	Consecutive Images had Different Exposure and Colour Balance	128
B1	Sketch of the Experiment Setup from Left View	145
B2	Sketch of the Experiment Setup from Top View	146
B3	Translated Projection Plane	148
G1	Subject 1 -Toy Bird	163
G2	Subject 2 - Toy Van	164
G3	Subject 3 - Toy Ogre	165
G4	Subject 4 - Toy Popcorn Booth	166
G5	Subject 5 - Spray Can	167
G6	Subject 6 - Ball	168
G7	Subject 7 - Can Drink	169
G8	Subject 8 - Glass	170
G9	Subject 9 - Candy Container	171
G10	Subject 10 - Rubik's Cube	172

## 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





© COPYRIGHT UPM

# 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 deduce 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.

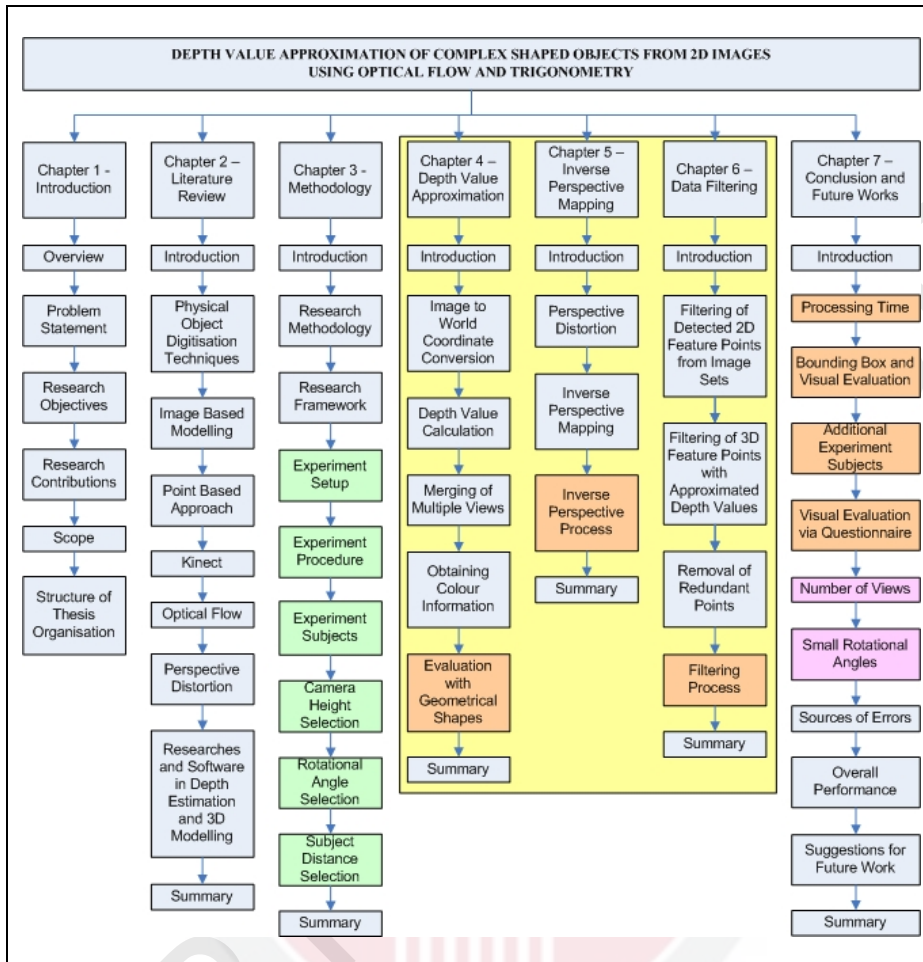
- Subjects of which images will be taken for the depth value estimation process must be rigid (does not deform from time to time), has features such as colours, textures and patterns on the surface to be detected, and not highly reflective or shiny. Parts that have the same colour as the setup's background 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.



## REFERENCES

- 3D scanners - A guide to 3D scanner technology*. (n.d.). Retrieved October 2, 2013, from Geomagic: <http://www.rapidform.com/3d-scanners/>
- Adam Technology. (2008). *Laser scanning vs digital photogrammetry*. Retrieved June 22, 2015, from <http://www.amerisurv.com/PDF/LaserScanningVsPhotogrammetry080108.pdf>
- Al-Ahmari, A., & Aalam, J. (2015). Optimizing parameters of freeform surface reconstruction using CMM. *64*, 17-28. doi:10.1016/j.measurement.2014.12.031
- Asada, N., Fujiwara, H., & Matsuyama, T. (1988). Edge and depth from focus. *International Journal of Computer Vision*, *26*(2), 153–163.
- Azevedo, T. C., Tavares, J. M., & Vaz, M. A. (2009). 3D object reconstruction from uncalibrated images using an off-the-shelf camera. In J. M. Tavares, & R. Jorge, *Advances in Computational Vision and Medical Image Processing* (pp. 117-136). Springer Science+Business Media B. V.
- Baker, S., Scharstein, D., Lewis, J., Roth, S., Black, M., & Szeliski, R. (2011). A database and evaluation methodology for optical flow. *International Journal of Computer Vision*, *92*(1), 1-31. doi:10.1007/s11263-010-0390-2
- Baltsavias, E. (2008). *Introduction to Airborne LiDAR and Physical Principles of LiDAR Technology (Lectures 1 and 5)*. Retrieved November 13, 2013, from Institute of Geodesy and Photogrammetry: <http://home.iitk.ac.in/~blohani/LiDARSchool2008/Downloads/Kanpur-Baltsavias.pdf>
- Bhattacharya, S., Idrees, H., Saleemi, I., Ali, S., & Shah, M. (2011). Moving object detection and tracking in forward looking infra-red aerial imagery. In R. Hammoud, G. Fan, R. McMillan, K. Ikeuchi, R. Hammoud, G. Fan, R. McMillan, & K. Ikeuchi (Eds.), *Machine Vision Beyond Visible Spectrum* (Vol. 1, pp. 221-252). Springer. doi:10.1007/978-3-642-11568-4
- Bouguet, J. (2000). *Pyramidal implementation of the Lucas-Kanade feature tracker: description of the algorithm. Technical report, OpenCV Document*. Intel Microprocessor Research Labs.
- Bradski, G., & Kaehler, A. (2008). *Learning OpenCV*. O'Reilly Media.
- Cao, X., Xiao, J., Foroosh, H., & Shah, M. (2006). Self-calibration from turn-table sequences in presence of zoom and focus. *Computer Vision and Image Understanding*, *102*, 227-237.



- Carl Zeiss Industrial Metrology. (n.d.). Retrieved February 26, 2012, from Carl Zeiss Industrial Metrology, LLC: [http://metrology.zeiss.com/industrial-metrology/en\\_us/products/systems/bridge-type-cmms/accura.html](http://metrology.zeiss.com/industrial-metrology/en_us/products/systems/bridge-type-cmms/accura.html)
- Chin, Y., Chao, T., & Rong, C. (2012). An improved obstacle detection using optical flow adjusting based on inverse perspective mapping for the vehicle safety. *International Symposium on Intelligent Signal Processing and Communication Systems (ISPACS 2012)* (pp. 85-89). IEEE.
- Connolly, C. (2007). Collision avoidance technology: from parking sensors to unmanned aircraft. *Sensor Review*, 27(3), pp. 182-188.
- Cui, Y., Schuon, S., Thrun, S., Stricker, D., & Theobalt, C. (2012). Algorithms for 3D Shape Scanning with a Depth Camera. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 1039-1050.
- Dai, F., Rashidi, A., Brilakis, I., & Vela, P. (2012). Comparison of image-based and time-of-flight-based technologies for three-dimensional reconstruction of infrastructure. *Journal of Construction Engineering and Management*, 139, 69-79.
- Desai, S., & Bidanda, B. (2006). Reverse engineering: A review & evaluation of contact based systems. In *Rapid Prototyping: Theory and Practice* (pp. 107-131). Springer US.
- Dictionary.com. (n.d.). *railroad*. Retrieved December 18, 2013, from Online Etymology Dictionary: <http://dictionary.reference.com/browse/railroad>
- Elberink, K. K. (2012). Accuracy and Resolution of Kinect Depth Data for Indoor Mapping applications. *Sensors*, 1437-1454.
- Eos Systems Inc. (n.d.). Retrieved November 25, 2013, from PhotoModeler: <http://www.photomodeler.com/products/modeler/default.html>
- Favaro, P. (2002, June 25). *Depth from focus/defocus*. Retrieved from [http://homepages.inf.ed.ac.uk/rbf/CVonline/LOCAL\\_COPIES/FAVARO1/dfdutorial.html](http://homepages.inf.ed.ac.uk/rbf/CVonline/LOCAL_COPIES/FAVARO1/dfdutorial.html)
- Fisher, B. (2002, January 23). *Shape from Silhouettes*. Retrieved from [http://homepages.inf.ed.ac.uk/rbf/CVonline/LOCAL\\_COPIES/MANESSIS/liter/node7.html](http://homepages.inf.ed.ac.uk/rbf/CVonline/LOCAL_COPIES/MANESSIS/liter/node7.html)
- Galeano, D., Devy, M., Boizard, J., & Filali, W. (2011). Real-time architecture on FPGA for obstacle detection using inverse perspective mapping. *International Conference on Electronics, Circuits and Systems (ICECS)* (pp. 788-791). Beirut: IEEE.
- Gelfand, N., Mitra, N., Guibas, L., & Pottmann, H. (2005). Robust global registration. *Symposium on geometry processing*, 2, p. 5.

- Gentilini, I., & Shimada, K. (2011). Predicting and evaluating the post-assembly shape of thin-walled components via 3D laser digitization and FEA simulation of the assembly process. *Computer-Aided Design*, 43(3), 316–328.
- Gibson, J. J. (1950). *The Perception of the Visual World*. Houghton Mifflin.
- Google. (n.d.). *Google Maps*. Retrieved November 25, 2013, from <https://maps.google.com/>
- Gupta, P., da Vitoria Lobo, N., & Laviola Jr., J. (2011). Markerless tracking and gesture recognition using polar correlation of camera optical flow. *Machine Vision and Applications*, 24, 651-666. Retrieved from <http://link.springer.com/article/10.1007/s00138-012-0451-3>
- Head & Face Color 3D Scanner (Model PS)*. (n.d.). Retrieved March 10, 2014, from Cyberware: <http://cyberware.com/products/scanners/ps.html>
- Highton, S. (2010). *Virtual Reality Photography: Creating Panoramic and Object Images*. Virtual Reality Photography.
- How It Works - The Steps & The Tech*. (n.d.). Retrieved March 10, 2014, from PhotoModeler: <http://www.photomodeler.com/products/how-it-works.html>
- How kinect depth sensor works - stereo triangulation?* (2010). Retrieved March 05, 2013, from Mirror Image - Mostly AR and Stuff: <http://mirror2image.wordpress.com/2010/11/30/how-kinect-works-stereo-triangulation/>
- Humphrey, G., Symons, L. A., Herbert, A. M., & Goodale, M. A. (1996). A neurological dissociation between shape from shading and shape from edges. *Behavioural Brain Research* 76, 117-125.
- Izadi, S., Kim, D., Hilliges, O., Molyneaux, D., Newcombe, R., Kohli, P., . . . Fitzgibbon, A. (2011). KinectFusion: Real-time 3D reconstruction and interaction using a moving depth camera. *ACM Symposium on User Interface Software and Technology (USIT)*, 559-568.
- Kaszynski, A., Beck, J., & Brown, J. (2013). Uncertainties of an automated optical 3D geometry measurement, modeling, and analysis process for mistuned integrally bladed rotor reverse engineering. *Journal of Engineering for Gas Turbines and Power*, 135(10), 102504 (8 pages).
- Kendoul, F., Fantoni, I., & Nonami, K. (2009). Optic flow-based vision system for autonomous 3D localization and control of small aerial vehicles. *Robotics and Autonomous Systems*, 57(6), 591–602.

- Kersten, D. (2010). *Shape from X*. Retrieved October 10, 2013, from Vision Research Laboratories - University of Minnesota: <http://vision.psych.umn.edu/users/kersten/kersten-lab/courses/Psy5036W2010/Lectures/16.%20Shape-from-X/16.ShapeFromX.nb.pdf>
- Khan, S. M., & Shah, M. (2008). Reconstructing non-stationary articulated objects in monocular video using silhouette information. *Computer Vision and Pattern Recognition* (pp. 1-8). IEEE.
- Kinect for windows*. (n.d.). Retrieved March 08, 2013, from Microsoft: <http://www.microsoft.com/en-us/kinectforwindows/Develop/New.aspx>
- Kinect for windows*. (n.d.). Retrieved March 4, 2013, from Microsoft: <http://www.microsoft.com/en-us/kinectforwindows/discover/features.aspx>
- Kinect for windows*. (n.d.). Retrieved March 5, 2013, from Microsoft: <http://www.microsoft.com/en-us/kinectforwindows/>
- Kinect hacking 105: Full resolution, public domain images of the speckle pattern*. (2010, November 18). Retrieved March 6, 2013, from Futurepicture: <http://www.futurepicture.org/?p=129>
- Kinect including kinect: Adventures!* (n.d.). Retrieved March 4, 2013, from Play.com: <http://www.play.com/Games/Xbox360/4-/10296372/Project-Natal/Product.html#jump-tech>
- Kinect*. (n.d.). Retrieved March 4, 2013, from Wikipedia: <http://en.wikipedia.org/wiki/Kinect>
- Kinect*. (n.d.). Retrieved March 5, 2013, from Xbox: <http://www.xbox.com/en-US/xbox360/accessories/kinect/Home>
- Koutsoudis, A., Vidmar, B., & Arnaoutoglou, F. (2013). Performance evaluation of a multi-image 3D reconstruction software on a low-feature artefact. *Journal of Archaeological Science*, 40(12), 4450-4456.
- Kraus, K. (2007). *Photogrammetry: Geometry from images and laser scans*. Deutsche Nationalbibliothek.
- Lanman, D., & Taubin, G. (2009). Build your own 3D scanner: 3D photography for beginners. In *ACM SIGGRAPH 2009 Courses* (p. 8). ACM.
- Lim, H. L. (2012). Putting Real-World Objects into Virtual World: Fast Automatic Creation of Animatable 3D models with a Consumer Depth Camera. *International Symposium on Ubiquitous Virtual Reality (ISUVR)* (pp. 38-41). IEEE.

- Liu, G., Wörgötter, F., & Markelic, I. (2013, March). Stochastic lane shape estimation using local image descriptors. *IEEE Transactions on Intelligent Transportation Systems*, 14, 13-21.
- Lookingbil, A. (2011). *Unsupervised learning and reverse optical flow in mobile robotics*. Stanford University.
- Menze, B., Stretton, E., Konukoglu, E., & Ayache, N. (2011). Image-based modeling of tumor growth in patients with glioma. In *Optimal control in image processing*. Heidelberg, Germany: Springer.
- Miano, J. (1999). *Compressed Image File Formats: JPEG, PNG, GIF, XBM, BMP*. Addison-Wesley Professional.
- Microsoft kinect teardown*. (2010, November 4). Retrieved March 5, 2013, from iFixit: <http://www.ifixit.com/Teardown/Microsoft+Kinect+Teardown/4066/2>
- Mohan, S., Simonsen, K. B., Balslev, I., Kruger, V., & Eriksen, R. D. (2011). 3D scanning of object surfaces using structured light and a single camera image. *International Conference on Automation Science and Engineering* (pp. 151-156). Trieste, Italy: IEEE.
- Muad, A. M., Hussain, A., Abdul Samad, S., Mustafa, M., & Majlis, B. (2004). Implementation of inverse perspective mapping algorithm for the development of an automatic lane tracking system. *TENCON 2004* (pp. 207-210). IEEE.
- New 3D laser scanner probe ideal for scanning mid-sized parts*. (n.d.). Retrieved October 7, 2013, from Laser Design and GKS: [http://www.laserdesign.com/products/scanners\\_and\\_software/high\\_precision\\_scanners/surveyor\\_ds-series/project\\_news/211/](http://www.laserdesign.com/products/scanners_and_software/high_precision_scanners/surveyor_ds-series/project_news/211/)
- Newcombe, R. A., & Davidson, A. J. (2010). Live dense reconstruction with a single moving camera. *Computer Vision and Pattern Recognition (CVPR)* (pp. 1498-1505). San Francisco, CA: IEEE.
- Newcombe, R., Izadi, S., Hilliges, O., Molyneaux, D., Kim, D., Davison, A., . . . Fitzgibbon, A. (2011). KinectFusion: Real-time dense surface mapping and tracking. *Mixed and Augmented Reality (ISMAR)* (pp. 127-136). Basel: 10th IEEE International Symposium.
- Nguyen, M., Wünsche, B., Delmas, P., & Lutteroth, C. (2012). 3D models from the black box: investigating the current state of image-based modeling. *Proceedings of the 20th International Conference on Computer Graphics, Visualisation and Computer Vision (WSCG 2012)*. Pilsen, Czech Republic.
- PhotoModeler Store*. (2013). Retrieved November 26, 2013, from PhotoModeler: <http://www.photomodeler.com/store/index.php?cPath=28>

- Pierrot-Deseilligny, M., De Luca, L., & Remondino, F. (2011). Automated image-based procedures for accurate artifacts 3D modeling and orthoimage generation. *Geoinformatics FCE CTU*, 6, 291-299.
- Rahmat, R., & Azmi, S. (2012). Depth value deduction using optical flow for reverse engineering. *Proceeding of IADIS International Conference Computer Graphics, Visualization, Computer Vision and Image Processing* (pp. 245-248). Rome, Italy: International Association for Development of the Information Society.
- Reichinger, A. (2011, April 3). *Kinect pattern uncovered*. Retrieved March 6, 2013, from azt.tm's Blog - Findings and Projects: <http://azttm.wordpress.com/2011/04/03/kinect-pattern-uncovered/>
- Remondino, F., & El-Hakim, S. (2006). Image-based 3D modeling: A review. *The Photogrammetric Record*, 21(115), 269–291.
- Riyad A. El-laithy, J. H. (2012). Study on the use of Microsoft Kinect for robotics applications. *Position Location and Navigation Symposium (PLANS)* (pp. 1280-1288). Myrtle Beach, SC: IEEE.
- Room lighting conditions for Kinect*. (n.d.). Retrieved March 8, 2013, from Xbox: <http://support.xbox.com/en-US/xbox-360/kinect/lighting>
- Roth, H., & Vona, M. (2012). Moving volume KinectFusion. *British Machine Vision Conference (BMVC)*, (pp. 1-11).
- Rusu, R., Marton, Z., Blodow, N., Dolha, M., & Beetz, M. (2008). Towards 3D point cloud based object maps for household environments. *Robotics and Autonomous Systems*, 56(11), 927-941. Retrieved from <http://www.willowgarage.com/sites/default/files/Rusu08RAS-Semantic.pdf>
- Scanning Devices Page*. (n.d.). Retrieved March 10, 2014, from ComputerSculpture.com: [http://computersculpture.com/Pages/Index\\_Scanning.html](http://computersculpture.com/Pages/Index_Scanning.html)
- Schouten, T., & van den Broek, E. (2008). Inverse perspective transformation for video surveillance. *International Society for Optics and Photonics*, 6814, pp. 681415-681415. doi:10.1117/12.767236
- Shi, J., & Tomasi, C. (1994). Good features to track. *IEEE Computer Society Conference on Computer Vision and Pattern Recognition* (pp. 593-600). IEEE.
- Tang, D., Yang, C., Zheng, J., Canton, G., Bach, R., Hatsukami, T., . . . Yuan, C. (2013). Image-based modeling and precision medicine - patient-specific carotid and coronary plaque assessment and predictions. *IEEE Transactions on Biomedical Engineering*, 60(3), 643-651.

- Taylor, C. A., & Steinman, D. A. (2008). Image-based modeling of blood flow and vessel wall dynamics: applications, methods and future directions. *Annals of Biomedical Engineering*, 38(3), 1188–1203.
- Tingdahl, D., & Van Gool, L. (2011). A public system for image based 3D model generation. Springer Berlin Heidelberg.
- Tingdahl, D., Vergauwen, M., & Van Gool, L. (2011). ARC3D: A public web service that turns photos into 3D models. In F. Stanco, S. Battiato, & G. Gallo, *Digital Imaging for Cultural Heritage Preservation: Analysis, Restoration, and Reconstruction of Ancient Artworks* (pp. 101-125). Boca Raton, Florida: CRC Press. Retrieved from [http://books.google.com.my/books?hl=en&lr=&id=QHnBxQ2xhGQC&oi=fnd&pg=PA101&dq=ARC3D&ots=6ibl8LQkck&sig=eITS0sz\\_zu3sJQefe-mTKBNiTUM&redir\\_esc=y#v=onepage&q=ARC3D&f=false](http://books.google.com.my/books?hl=en&lr=&id=QHnBxQ2xhGQC&oi=fnd&pg=PA101&dq=ARC3D&ots=6ibl8LQkck&sig=eITS0sz_zu3sJQefe-mTKBNiTUM&redir_esc=y#v=onepage&q=ARC3D&f=false)
- Tong, J., Zhou, J., Liu, L., Pan, Z., & Yan, H. (2012). Scanning 3D full human bodies using kinects. *IEEE Transactions on Visualization and Computer Graphics*, 18(4), 643 - 650.
- VISICS Research Group of the University of Leuven. (n.d.). *ARC 3D Webservice*. Retrieved November 25, 2013, from Arc 3D: <http://www.arc3d.be/>
- Wang, L., Vanderhout, R., & Shi, T. (2012). *Computer Vision Detection of Negative Obstacles with the Microsoft Kinect*. The University of British Columbia.
- Wehr, A., & Lohr, U. (1999). Airborne laser scanning—an introduction and overview. *ISPRS Journal of Photogrammetry and Remote Sensing*, 54(2), 68-82.
- Whole Body Color 3D Scanner (Model WBX)*. (n.d.). Retrieved March 10, 2014, from Cyberware: <http://cyberware.com/products/scanners/wbx.html>
- Xiao, J., Fang, T., Zhao, P., Lhuillier, M., & Quan, L. (2009). Image-based street-side city modeling. *ACM Transactions on Graphics (TOG) - Proceedings of ACM SIGGRAPH Asia*, 28(5), 114.
- Yang, J. (2013). Image-based procedure for biostructure modeling. *Journal of Nanomechanics and Micromechanics*, 4(3), B4013001.
- Zhang, R., Tsai, P.-S., Cryer, J. E., & Shah, M. (1999). Shape from shading: A survey. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 21(8), 690-706.
- Zingg, S., Scaramuzza, D., Weiss, S., & Siegwart, R. (2010). MAV navigation through indoor corridors using optical flow. *International Conference on Robotics and Automation* (pp. 3361-3368). Anchorage, Alaska: IEEE.