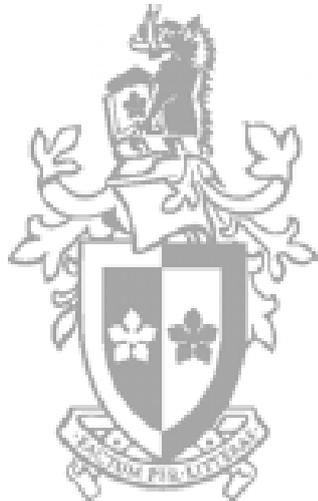


# **Large-scale Range Data Acquisition and Segmentation**

**Reyhaneh Hesami**

**Submitted in total fulfilment of  
the requirements for the degree of  
Doctor of Philosophy**



**Faculty of Engineering and Industrial Sciences  
Swinburne University of Technology  
2009**

# Abstract

The research reported in this thesis aims to devise a cost-effective, robust technology and technique for accurately measuring and segmenting geometric details embedded in the exterior surfaces of large buildings. A diverse range of applications become viable or significantly enhanced by capturing the accurate geometric data of significant buildings and extracting the fine details of such data. Motivations for this thesis stem from the facts that commercially available large-scale data acquisition systems are expensive and existing algorithms for 3D data processing are yet to address the processing complexity associated with the 3D segmentation of large outdoor objects.

The contributions of this thesis are threefold. First, a low-cost versatile large-scale rangescanner, capable of capturing range data up to 300 metres, is designed and implemented. An innovative method for system calibration and the data fusion of the intensity and range measurements has been developed. A number of experiments are also conducted to evaluate the performance of the proposed rangescanner system and the data fusion technique. The range data obtained by the rangescanner system has been verified using two methods of verification — *application checking* and *equivalence checking*. Example results of the verification, presented in this thesis, shows that the laser rangescanner device is capable of providing adequate accuracy and resolution for large-scale civil application with minimum complexity and cost. The design provides portability, flexibility and ease of operation. Secondly, problems associated with range data acquisition and processing of large building exteriors are studied. Key challenges of processing the range data of large buildings, including significant disparities in the size and depth and the existence of substantial construction error in historical buildings, have been identified and their effects for the segmentation task are examined. Thirdly, a computationally effective and robust segmentation technique, capable of extracting geometric details of large building

exteriors, is developed. The segmentation algorithm, titled *Hierarchical Robust Segmentation (HRS)*, uses a high breakdown, robust estimator in a hierarchical coarse-to-fine approach. This algorithm is then tested on several range data sets obtained by different laser rangescanners. The experimental results show that the proposed algorithm overcomes most of the current problems of large-scale data segmentation presented in this thesis by extracting both coarse and fine details from range data of large building exteriors in a relatively short period of time.

# Acknowledgement

*"If I have seen further, it is by standing on the shoulders of giants."*

**-Isaac Newton**

First and foremost, I would like to express my deepest gratitude and appreciation to my supervisor, Associate Professor Alireza Bab-Hadiashar for his mentoring and friendship throughout my candidature. He introduced computer vision to me and without his constant support I could not have finished this thesis. I thank my first co-supervisor Dr. Hanes Van Der Walt who was always cheerful and encouraging. I also thank Dr. Reza Hosseinezhad who stepped in as my co-supervisor midway through this project. We had fruitful discussions through the last stage of my research.

I would also like to thank Professor Ray Jarvis, Professor David Suter and his research team at Monash University, Melbourne, Australia, for providing access to their Riegl laser rangescanner and several sets of range data captured from Monash University buildings. Thank you is also due to Professor Peter Allen and Mr Paul Blaer of Columbia University, USA, for providing me with range data of Notre Dome Church in France. I thank Mr Babak Majidi for his help in data acquisition of Melbourne Exhibition Building.

There are also technical and support staff members at Swinburne University who have supported this study, particularly Mr Walter Chetcuti, Mr Warren Gooch and Ms Nancy Moncrieff. I also thank Ms Dionne C Eagleson for her proofreading services.

My sincere thanks and appreciations go to my teachers, my friends and family. They made me what I am. Specially, to my devoting parents who have been my source of inspiration and strength, I am forever indebted for their countless support and sacrifices. I would like to particularly thank my mum, my first teacher, who started teaching me maths and alphabets

when I was as young as three. I thank my younger brothers Ali, Ehsan and Erfan for their encouragement.

When one takes on a project of this size, it is going to affect those people who are near and dear. I owe the completion of this dissertation to the support, camaraderie, and encouragement of my husband Dr. Payam Ghadirian over the years of my study. To Pouya, my son, who has been grown up with this project, for his patient and understanding as a very young boy, when mum was busy working late on her PhD!

**Dedicated to:**

*My parents, Pouya and Payam*

## Declaration

This dissertation is submitted to Swinburne University of Technology in fulfilment of the requirements for the degree of Doctor of Philosophy. I hereby declare that this dissertation is entirely my own work and contains no material previously published or written by another person, except where otherwise mentioned. Parts of the work described in Chapter three, four and five have previously appeared or currently under review in the following conference or journal papers:

**Hesami R.**, Bab Hadiashar A., Hosseinnejad R., “*A Robust Hierarchical Technique for Automatic Range Segmentation of Large Building Exteriors*”, Submitted to the Journal of Computer Vision and Image Understanding (CVIU), December 2007

**Hesami R.**, Bab Hadiashar A., Hosseinnejad R., “*A Novel Hierarchical Technique for Range Segmentation of Large Building Exteriors*”, International Symposium of Visual Computing (ISVC), November 2007, Nevada, USA. Appear in Lecture Notes in Computer Science, No. 4842, pages 75-85.

**Hesami R.**, Bab Hadiashar A., Gheissari N., “*Large Object Range Data Acquisition, Fusion and Segmentation*”, Digital Image Computing Techniques and Application, DICTA’05, December 6-8, Cairns, Australia

Reyhaneh Hesami  
2009

# Table of Content

<b>Abstract</b> .....	<b>i</b>
<b>Acknowledgement</b> .....	<b>iii</b>
<b>Declaration</b> .....	<b>vi</b>
<b>Table of Content</b> .....	<b>vii</b>
<b>List of Figures</b> .....	<b>xi</b>
<b>List of Tables</b> .....	<b>xviii</b>
<b>Chapter 1 Introduction</b> .....	<b>1</b>
<b>1.1 Background and motivation</b> .....	<b>1</b>
<b>1.2 What particularly is a complicated problem?</b> .....	<b>4</b>
<b>1.3 Aim</b> .....	<b>6</b>
<b>1.4 Methodology</b> .....	<b>7</b>
<b>1.5 Contributions of the thesis</b> .....	<b>8</b>
<b>1.6 Overview of the study</b> .....	<b>9</b>
<b>Chapter 2 3D Measurement</b> .....	<b>11</b>
<b>2.1 Introduction</b> .....	<b>11</b>
<b>2.2 3D measurement systems</b> .....	<b>12</b>
2.2.1 Triangulation based rangescanner systems .....	13
2.2.1.1 Passive triangulation (stereovision) .....	14
2.2.1.2 Active triangulation.....	15

2.2.2	Time-of-flight based rangescanner systems.....	16
2.2.2.1	Non-scanning 3D TOF cameras.....	19
2.2.2.2	Scanning 3D TOF cameras (3D laser scanners) .....	20
2.2.3	Triangulation vs. laser TOF based rangescanners.....	24
<b>2.3</b>	<b>Range and intensity data integration .....</b>	<b>30</b>
2.3.1	Feature-based range and intensity data fusion .....	31
2.3.2	System-based range and intensity data fusion .....	35
<b>2.4</b>	<b>Chapter review .....</b>	<b>37</b>
	<b>Chapter 3 Range Image Segmentation .....</b>	<b>39</b>
<b>3.1</b>	<b>Introduction .....</b>	<b>39</b>
<b>3.2</b>	<b>Range segmentation .....</b>	<b>40</b>
<b>3.3</b>	<b>Taxonomy of range segmentation algorithms .....</b>	<b>43</b>
3.3.1	Edge detection based range segmentation algorithms .....	44
3.3.2	Region growing based range segmentation algorithms .....	45
3.3.3	Parametric fitting-based range segmentation algorithm .....	46
3.3.3.1	Modified Selective Statistical Estimator (MSSE).....	51
3.3.4	Combined methods .....	55
<b>3.4</b>	<b>Range segmentation of large man-made objects.....</b>	<b>56</b>
<b>3.5</b>	<b>Chapter review .....</b>	<b>60</b>
	<b>Chapter 4 Laser Rangescanner System .....</b>	<b>62</b>
<b>4.1</b>	<b>Introduction .....</b>	<b>62</b>
<b>4.2</b>	<b>Laser rangescanner system design .....</b>	<b>62</b>
4.2.1	Hardware architecture .....	63
4.2.2	Software architecture .....	66
4.2.3	Automatic system calibration.....	67
4.2.4	Range and intensity data fusion .....	71
4.2.4.1	Camera models.....	71
4.2.4.2	Camera calibration .....	76
4.2.4.3	System calibration verification for fusion.....	79

<b>4.3</b>	<b>Laser rangescanner system experimental results.....</b>	<b>80</b>
<b>4.4</b>	<b>Laser rangescanner system characterisation .....</b>	<b>85</b>
4.4.1	Rangefinder errors.....	85
4.4.1.1	Temperature effect on the laser hardware system.....	86
4.4.1.2	Surrounding temperature effect.....	86
4.4.1.3	Range accuracy at different distances .....	88
4.4.1.4	Mixed Pixel effects .....	90
4.4.1.5	Target reflectance properties.....	92
4.4.2	PTU Errors .....	93
<b>4.5</b>	<b>Verification of the functionality of the 3D scanner system .....</b>	<b>95</b>
4.5.1	Application checking verification of 3D measurement system .....	96
4.5.2	Equivalence checking verification of 3D measurement system .....	100
<b>4.6</b>	<b>Chapter Review .....</b>	<b>105</b>
<b>Chapter 5 Range Data of Large Building Exteriors.....</b>		<b>109</b>
<b>5.1</b>	<b>Introduction .....</b>	<b>109</b>
<b>5.2</b>	<b>Characteristics of range data of building exteriors .....</b>	<b>109</b>
5.2.1	Existence of moving objects .....	110
5.2.2	Disparity in size .....	111
5.2.3	Existence of very fine details .....	114
5.2.4	High uncertainty due to the construction errors.....	116
<b>5.3</b>	<b>Chapter review .....</b>	<b>118</b>
<b>Chapter 6 Hierarchical Robust Range Segmentation .....</b>		<b>120</b>
<b>6.1</b>	<b>Introduction .....</b>	<b>120</b>
<b>6.2</b>	<b>From robust estimation to robust segmentation .....</b>	<b>121</b>
<b>6.3</b>	<b>Hierarchical Robust Segmentation scheme .....</b>	<b>122</b>
6.3.1	How does the hierarchical scheme reduce computation costs? .....	126
<b>6.4</b>	<b>Experimental results .....</b>	<b>127</b>
6.4.1	Synthetic data .....	127

6.4.2	Real data.....	132
6.5	Chapter review .....	139
<b>Chapter 7 Conclusions and Future Directions.....</b>		<b>140</b>
7.1	Conclusions .....	140
7.2	Future directions .....	142
<b>Bibliography .....</b>		<b>144</b>
<b>Appendices .....</b>		<b>166</b>

# List of Figures

## Chapter 1

Figure 1.1: A typical computer vision system .....	2
Figure 1.2: Royal Melbourne Exhibition Building, Melbourne, Australia: cars, passengers and vegetation are obstacles that can not be avoided at the time of data collection. ....	4
Figure 1.3: Examples of disparity in the size of various features. Different colours show different features. ....	5
Figure 1.4: Effect of a construction error on the range segmentation of a large building: (a) Walls of the front side of the Shrine of Remembrance building (coloured in blue) seem coplanar. (b) Accurate ground truth measurement prove they are two separate planar surfaces. It is shown in the hypothetical top view of the building. ....	6
Figure 1.5: Steps of the research.....	8

## Chapter 2

Figure 2.1: A classification of 3D measurement techniques based on [16] and [17]. ....	12
Figure 2.2: Passive triangulation (Stereovision) .....	14
Figure 2.3: Active triangulation.....	15
Figure 2.4: A typical active triangulation–based rangescanner .....	16

Figure 2.5: Non-scanning 3D TOF camera: (a) Principle (Adapted from [33] (b) Commercialised, manufactured by MESA imaging ( <a href="http://www.mesa-imaging.ch/">http://www.mesa-imaging.ch/</a> ).....	19
Figure 2.6: Principle of 3D laser scanner operation manufactured by Riegl ( <a href="http://www.riegl.com">www.riegl.com</a> ) .....	20
Figure 2.7 An example of laser rangescanner based on pulse TOF (Adapted from [44]) .....	21
Figure 2.8: Laser rangescanner adapted from [49]. The scanner consisted of (a) an 8-foot vertical truss, (b) a 3-foot horizontal arm, (c) a pan (d) and a tilt assembly (d) and a scan head (e) that mounted on the pan-tilt assembly. ....	24
Figure 2.9: Laser footprint shape and size changes with beam incident angle, $\alpha$ , and divergence, $\beta$ . ....	28
Figure 2.10: Mixed pixel effect.....	29
Figure 2.11: An example of feature base range and intensity data fusion. This method has been used for 3D modelling of large-scale scene (adapted from[63]) .....	32
Figure 2.12: An example of feature- based range and intensity data fusion (adapted form [25]) .....	34
 <b>Chapter 3</b>	
Figure 3.1: Range image of a polyhedral object (right) and its intensity image (left).....	40
Figure 3.2: Segmentation of range data illustrated in Figure 3.1: (left) correct segmentation, (middle) under-segmentation and (right) over-segmentation. ....	43
Figure 3.3: Range segmentation into planar and quadric, adapted from [112] (a) pre-processing and (b) surface extraction.....	49
Figure 3.4: Robust segmentation using MSSE. The process has two parts of estimation and segmentation .....	52
Figure 3.5: The front view of the Royal Melbourne Exhibition Building, Melbourne, Australia: (top) intensity image, (bottom) colour-coded range image.....	57

Figure 3.6: Semantic net model for the architectural scene (adapted from [142]). Nodes represent the model entities (e.g. walls, roofs, floors) and are linked by architectural relationships (e.g. parallelism and orthogonality).....	59
---	----

## Chapter 4

Figure 4.1: Laser rangescanner system: (top) Overall system architecture (middle) System alignment ( $r \gg d$ , $O_c$ is the centre of camera coordinate system and $O_l$ is the centre of LRF coordinate system) (bottom) Experimental system set-up .....	64
Figure 4.2: Laser rangescanner system: Software architecture.....	66
Figure 4.3: System set-up for automatic system calibration procedure .....	68
Figure 4.4: Automatic system calibration .....	69
Figure 4.5: Intrinsic camera parameters in a pinhole camera model. $\Phi$ and $R$ are focal and image planes, respectively. $c$ is the camera principle point and $f$ is the camera focal length. $(O_c, X_c, Y_c, Z_c)$ is the coordinate system of camera and $(c, u, v)$ is the coordinate system in the image plane. ....	72
Figure 4.6: Pinhole camera vs. real camera (adapted from [152])......	76
Figure 4.7: Plot of calibration validation result in y direction. ....	80
Figure 4.8: System works! .....	81
Figure 4.9: Intensity image and colour-coded range image captured from the exterior of AR building (Swinburne University of Technology, Melbourne, Australia). ....	82
Figure 4.10: Royal Melbourne Exhibition Building: (a) Intensity image (720×576 pixels) (b) Colour-coded range image (715×400 pixels) (c) Range and intensity data fusion (720×400 pixels). The areas coloured in white by the fusion algorithm shows that algorithm could not find any valid range or intensity data.....	83
Figure 4.11: The Shrine of Remembrance, Melbourne, Australia: (a) Intensity image (720×576 pixels) (b) Colour-coded range image (715×400 pixels) (c) Range and intensity	

data fusion (720×400 pixels). The areas coloured in white by the fusion algorithm shows that algorithm could not find any valid range or intensity data. ....	84
Figure 4.12: Measurement fluctuations over time due to temperature effect on laser rangefinder electronics. ....	86
Figure 4.13: Range measurements vs. temperature at distances of nine and nineteen meters	87
Figure 4.14: Comparison of the variance and RMS error for five different distances. ....	90
Figure 4.15: Range image of the front side of the Shrine of Remembrance building, Melbourne, Australia: (a) edges appears as sawtooth due to the mixed pixel effect, (b) mixed pixel effect in the part of the three cross sections of the range image, between columns 250 and 500 (row 240 appears in red, row 250 appears in cyan and row 260 appears in green)..	91
Figure 4.16: Comparison of target property effects on range measurement. ....	92
Figure 4.17: System set-up to determine errors in PTU measurement: (left) horizontal angular resolution (HAR) and (right) vertical angular resolution (VAR). In this experiment, the distance from target (D) measures 1520 centimetres by LRF. ....	94
Figure 4.18: Laser rangescanner system verification. ....	95
Figure 4.19: Application checking verification of laser rangescanner system. ....	96
Figure 4.20: The Royal Melbourne Exhibition Building: a) colour-coded range image (715×400) pixels, b) intensity image (715×400) pixels, and c) range segmentation result. Different colour shades in grey-scale shows each segment. ....	98
Figure 4.21: The Shrine of Remembrance: a) colour-coded range image (715×400) pixels; b) intensity image (715×400) pixels; and c) range segmentation result. Different colour shades in grey-scale show each segment. ....	99
Figure 4.22: Equivalence checking verification of laser rangescanner system. ....	100

Figure 4.23: Range images of the front side of the Shrine of Remembrance, Melbourne, Australia: (a) obtained by the Riegl laser rangescanner (b) obtained by the experimental laser rangescanner .....	101
Figure 4.24: Range images of the front side of the Royal Melbourne Exhibition Building, Melbourne, Australia: (a) obtained by the Riegl laser rangescanner (b) obtained by the experimental laser rangescanner .....	101
Figure 4.25: Corresponding features of the range images of the Shrine of Remembrance, Melbourne, Australia obtained by: (a) Riegl laser rangescanner (b) Experimental laser rangescanner .....	102
Figure 4.26: Corresponding features of the range images of the Royal Melbourne Exhibition Building, Australia obtained by: (a) Riegl laser rangescanner (b) Experimental laser rangescanner .....	103
Figure 4.27: Fine details embedded in the pediment and frieze of the Shrine of Remembrance building.....	107
<b>Chapter 5</b>	
Figure 5.1: Intensity and range images of the Royal Melbourne Exhibition Building. Cars, passengers and vegetation are obstacles that are unavoidable at the time of data collection. Moving objects appear as straight lines in the range image.....	110
Figure 5.2: The front view of the Shrine of Remembrance building. Large disparities in the size of features are highlighted in different colours. This building is obviously composed of a collection of large, medium and very small structures.....	111
Figure 5.3: a) A sample of the synthetic data used to demonstrate the effect of disparity in size for large-scale range data segmentation. b) A plot representing the percentage of success in segmenting both small and large structures with a robust estimator versus the ratio of the size of small structure to the size of whole population for different values of K. ....	113
Figure 5.4: Fine details in the façade of the Shrine of Remembrance building.....	114

Figure 5.5: Plot representing the number of required random samples versus the minimum relative size of the smallest desired detail for different probabilities of success in 3D. The number of required samples enormously increases when the size of desired structure is less than 10 per cent. .... 116

Figure 5.6: a) Sample of the synthetic data used for segmentation analysis of distant co-planar surfaces. b) Likelihood of detecting co-planar surfaces as one segment vs. distance of structures for cases where  $K=0.1$ . .... 118

## Chapter 6

Figure 6.1: Inputs and outputs of MSSE as segmentor ..... 124

Figure 6.2: Cascade of Hierarchical Robust Segmentation (HRS).  $K$  is the relative size of smallest structure to be segmented.  $\sigma$  is range accuracy of measurement system and is varied by instrument. .... 125

Figure 6.3: Example of synthetic data with multiple structures. In this example, total number of data including gross outliers is 2,270 points; number of gross outliers is 30 points and size of the smallest structure is 40 points (1.7 per cent of the entire data)..... 128

Figure 6.4: Segmentation result for dataset presented in Figure 6.1 where  $P$  is set to 0.85 and  $K$  (size of smallest structure) is set to 0.05. .... 129

Figure 6.5: First level of robust segmentation. .... 131

Figure 6.6: Second level of robust segmentation..... 131

Figure 6.7: Third level of robust segmentation..... 132

Figure 6.8: Hierarchical range segmentation of the front side of the Shrine of Remembrance, Melbourne – Australia. Range data of the building is captured by Riegl (LMS-Z210) laser rangescanner: a-left) Intensity image, a-right) Range image, b) First level of segmentation, c) Final result of hierarchical segmentation. d) All possible detail (planar and decorative) of the pediment is successfully segmented. This figure is best viewed in colour. .... 133

Figure 6.9: Hierarchical segmentation of the back side of the Melbourne Exhibition Centre – Australia. Range data of the building is captured by the experimental laser rangescanner

explained in Chapter 3: a) Intensity image of the building. b) First level of segmentation (coarse segmentation). c) Final result of hierarchical segmentation. This figure is best viewed in colour. .... 137

Figure 6.10: Hierarchical segmentation of the south view of Notre-Dam Church – France. Range data of the church captured by Leica HDS2500 laser rangescanner. a) Intensity image of the church [172]. b) First level of segmentation (coarse segmentation). c) Final result of hierarchical segmentation d, e, f) All possible details (planar and decorative) of different parts of building are successfully segmented. This figure is best viewed in colour. .... 138

## List of Tables

Table 2.1: Commercial laser rangescanners based on triangulation.....	26
Table 2.2: Examples of commercial laser rangescanners based on time-of-flight.....	27
Table 4.1: Technical specification of LRF ( <a href="http://www.mdl.co.uk">http://www.mdl.co.uk</a> ).....	65
Table 4.2: Technical specification of PTU ( <a href="http://www.dperception.com/">http://www.dperception.com/</a> ).....	65
Table 4.3: System calibration parameters .....	70
Table 4.4: Camera calibration parameters: estimated vs. expected .....	77
Table 4.5: Calibration validation result for eight distances .....	80
Table 4.6: Range accuracy at different distances and statistical values of range measurements .....	88
Table 4.7: PTU angular errors.....	94
Table 4.8: Comparison of estimated corresponding line segments of range image obtained by Riegl and experimental laser rangescanner (image of the Shrine of Remembrance) .....	104
Table 4.9: Comparison of estimated corresponding line segments of range image obtained by Riegl and experimental laser rangescanner (image of the Royal Melbourne Exhibition Building) .....	104

Table 6.1: Outcome of direct implementation of the robust range segmentation algorithm for the range data of the Shrine of Remembrance with different values of K (size of the smallest structure) .....	134
Table 6.2: Outcome of hierarchical implementation of robust segmentation algorithm for the range data of the Shrine of Remembrance .....	135