UNIVERSITI PUTRA MALAYSIA

AN ENSEMBLE MODELING APPROACH FOR BIRD NEST COUNTING AND 3-D CAVE MODELLING AT GOMANTONG, SABAH, MALAYSIA USING TERRESTRIAL LASER SCANNING

MOHAMMED OLUDARE IDREES

FK 2018 11

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By

MOHAMMED OLUDARE IDREES

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

September 2017

DEDICATION

In memory of my late grandfather, Haj. Mohammed Aladuge and my late uncle, Mualim Mohammed Sullaiman, for being the bedrock of my early upbringing and education.

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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MOHAMMED OLUDARE IDREES

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Chairman : Professor Biswajeet Pradhan, PhD
Faculty : Engineering

As far back as early 15th century during the reign of the Ming Dynasty (1368 to 1634), Gomantong cave in Sabah, Malaysia, has been known as one of the largest roosting sites for swiftlet birds (*Aerodramus maximus and Aerodramus fuciphagus*) and wrinkle-lipped bats (*Chaerephon plicatus*) in very large colonies. Until recently, no study has been done to estimate the colony sizes of these inhabitants in spite of the grave danger posed to them by human activities and potential loss of the cave to post-speleogenetic deformation. In this study, high resolution terrestrial laser scanning data was used to (i) detect and count bird-nests in cave, (ii) model the cave in three-dimensional (3D) geometry at different resolution scales and (iii) to analyze the cave passage geomorphology. The proposed ensemble modelling approach integrates Taguchi and Objective Function optimization techniques to optimize image segmentation parameters - scale, shape, and compactness. The resulting image objects were classified as birds-nest and cave-wall by exploiting the laser return intensity and the size of image objects. Thereafter, the detection accuracy, reliability and transferability of the method were evaluated. For geometric reconstruction, 3D model of the cave was generated at two resolution scales by using meshing and textured 3D rendering. The models allow investigating the passage network structure, morphometry, geologic rock structure and macro- and micro-geomorhpological features. Result of the detection accuracy yielded area under the ROC curve (AUC) of 0.93 and $P<0.0001$ at 95% confidence level. Similarly, the tests of heterogeneity using Cochran's Q and Inconsistency I^2 produced p-value of 0.384 and I^2 value of 5.10% at 95% confidence interval respectively. Also, the transferability assessment produced overall accuracies of 0.93 and 0.94 AUC and $p<0.0001$ at 95% confidence level using the two image scenes taken from the lower and upper caves respectively. From the nine image scenes used for testing and validation, 36,088 bird-nests were counted. The 3D mesh model allows visualizing and characterising the general geomorphological

complexity of the entire cave network, internally and externally in 3D space. Furthermore, mesh model permits extracting detail profiles and cross sections in their geometrically correct dimensions, analyzing the cave's structure and morphometry. On the other hand, textured 3D rendering offers true-to-life visualization of all the fine geometric details and complete representation of the cave's interior "infrastructure" at sub-millimetres accuracy. It allows discerning different speleogenetic phases, karstification processes and micro-morphologies such as wall and ceiling seepage, hanging rocks, fractures, scallops, ceiling flush dome, pockets, bell-hole and avens. Besides, the texture model permits identification of cave arts and engravings along the passages. Point cloud-based analysis of passage rock discontinuity shows that the formations of the cave channels have been influenced by strike, dip/direction and bedding planes. Potentially, passage failure is predicted along east-west, west-east and southeast-northwest. This investigation reveals that Gomantong cave passage developments were largely controlled by the geologic rock structure; some of the conduits still retain their original phreatic tube formation while majority have been largely modified.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

SATU PENDEKATAN MODEL HIMPUNAN UNTUK PENGIRAAN SARANG BURUNG DAN PEMODELAN 3-DIMENSI GUA DI GOMANTONG, SABAH, MALAYSIA MENGGUNAKAN IMBASAN LASER TERESTRIAL

Oleh

MOHAMMED OLUDARE IDREES

September 2017

Pengerusi : Profesor Biswajeet Pradhan, PhD
Fakulti : Kejuruteraan

Seawal abad ke-15, sewaktu pemerintahan Dinasti Ming (1368 ke 1634), gua Gomantong di Sabah, Malaysia, dikenali sebagai salah satu lapangan persarangan sarang burung(*Aerodramus maximus dan Aerodramus fuciphagus*) dan kelawar bermukut kedut (*Chaerephon plicatus*) yang mempunyai koloni yang sangat besar. Akhir-akhir ini, tidak ada kajian yang dibuat untuk menganggarkan saiz koloni haiwan-haiwan ini walaupun terdapat risiko yang tinggi disebabkan oleh kegiatan manusia dan potensi kehilangan gua kepada deformasi pasca-speleogenetik. Dalam kajian ini, data imbasan laser terestrial beresolusi tinggi digunakan untuk (i) mengesan dan mengira sarang burung dalam gua (ii) memodelkan gua dalam geometri tiga dimensi (3D) pada skala resolusi yang berbeza (iii) untuk menganalisa geomorfologi saluran gua. Pendekatan model himpunan yang disarankan menggabungkan teknik-teknik pengoptimuman Kefungsian Taguchi dan Objektif untuk mengoptima parameter segmentasi imej – skala, bentuk dan kepadatan. Objek-objek imej yang terhasil diklasifikasikan sebagai sarang burungdan dinding gua dengan cara mengeksploitasi keamatan pulangan laser dan saiz objek imej. Selepas itu, ketepatan pengesanan, kebolehpercayaan dan kebolehalihan metod telah dinilai. Untuk rekonstruksi geometri, model 3D gua dijana pada dua skala resolusi dengan menggunakan jaringan dan pentafsiran 3D bertekstur. Model-model berkenaan membolehkan struktur jaringan laluan, morfometri, struktur batu geologik dan ciri-ciri makro dan mikro geomorfologi dikaji. Keputusan ketepatan pengesanan di bawah lengkuk ROC (AUC) adalah 0.93 dan P<0.0001 pada aras keyakinan 95%. Ujian keheterogenan menggunakan ujian-ujian Cochran's Q and Inconsistency I^2 menghasilkan nilai P = 0.384 dan nilai I^2 5.10% pada sela keyakinan 95%.. Penilaian kebolehalihan menghasilkan keseluruhan ketepatan 0.93 dan 0.94 AUC dan nilai p<0.0001 pada aras keyakinan 95% menggunakan dua senario imej yang diambil dari

gua bawah dan atas. Daripada sembilan senario imej digunakan untuk ujian dan pengesahan, sejumlah 36,088 sarang burungtelah dikira. Jaring 3D memberikan pembentangan digital interaktif yang membolehkan visualisasi dan pencirian kompleksiti morfologi umum keseluruhan jaringan gua, luar dan dalam, dalam ruang 3 dimensi. Tambahan pula, model jaringan membenarkan pengestrakan profil dan keratan rentas secara terperinci dalam dimensi yang geometrinya tepat, mengkaji struktur dan morfometri gua. Sebaliknya, model tekstur 3D juga menawarkan visualisasi yang seolah-olah nyata mengandungi perincian halus geometri dan pembentangan lengkap bahagian dalaman "infrastruktur" gua pada ketepatan sub-milimeter yang mustahil untuk diperolehi dengan pemerhatian langsung atau dari model jaringan. Ia membolehkan fasa-fasa pengesanan speleogenetik, proses karstifikasi, dan mikro-morfologi seperti tirisan dinding dan syiling, batu tergantung, retakan, skalop, siling kubah sama rata, poket, lubang loceng dan aven. Di samping itu, model tekstur membenarkan pengenalpastian seni gua dan lakarannya di sepanjang laluan. Analisis titik awan ketidakselanjaran batu laluan menunjukkan bahawa pembentukan saluran gua dipengaruhi oleh ketukan, kecondongan/arah dan satah perlapisan. Kegagalan laluan berpotensi diramalkan di sepanjang timur-barat, barat-timur, dan selatan-utara. Ringkasnya, kajian ini menunjukkan bahawa pembangunan gua Gomantong banyak dikawal oleh struktur batu geologi; kebanyakan konduit masih mengekalkan formasi tiub preatik asal mereka sementara majoritinya banyak yang telah diubahsuai.

ACKNOWLEDGEMENTS

All praises and adoration belong to almighty Allah, the ever gracious and the most merciful, for His abundant favours, grace and guidance at all moment of my life and particularly for the successful completion of this doctoral programme. To my parents and family, I feel, with every sense of humility, your moral and spiritual backing with your constant prayers to God for my success. Without the unflinching encouragement, solid supports and sacrifices by my adorable and courageous partner, Nikky, and my children (Naimy, Fari and Mujib), the journey would have been prolonged.

I am taking this golden opportunity to express my profound gratitude and deep regards to my supervisor, Prof. Dr. Biswajeet Pradhan, for his exemplary guidance, mentoring and encouragement even before and during the course of this PhD programme. He is a visionary guide with classic model that will keep me resonating up the pedestal of career excellence for a lifelong. Without his moral, intellectual and financial supports through the UPM Graduate Research Assistance Scholarship, it would have been impossible for me to accomplish this doctoral research.

I wish also to assert my obliged appreciation to my supervisory committee members, Assoc. Prof. Dr. Helmi Zulhaidi bin Mohd Shafri and Assoc. Prof. Dr. Siti Khairuniza Binti Bejo for the vital information provided in their respective fields and their cooperation towards successful completion of this research. I am also grateful to other faculty members including Prof. Shattri Mansor, Assoc. Prof. Dr. Zainuddin bin Md Yusoff for making themselves available for consultation.

My heartfelt thanks to my special friend and brother, Wale Otuseso, for been a root in my life, I remain ever grateful for your assistance, financial and moral. To all my colleagues, I wish to say I admire your cooperation and scholarly friendship. Because of time and space, it is impossible to mention everybody who had contributed in one way or the other, I remain ever grateful to you all.

I certify that a Thesis Examination Committee has met on 27 September 2017 to conduct the final examination of Mohammed Oludare Idrees on his thesis entitled "An Ensemble Modelling Approach for Bird Nest Counting and 3-D Cave Modelling at Gomantong, Sabah, Malaysia using Terrestrial Laser Scanning" 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:

Gorakanage Arosha Chandima Gomes, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Aimrun Wayayok, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Abd. Rahman bin Ramli, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Armando A. Apan, PhD
Professor
University of Southern Queensland
Australia
(External Examiner)

NOR AINI AB. SHUKOR, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 28 December 2017

This thesis was submitted to the Senate of the 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:

Biswajeet Pradhan, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Helmi Zulhaidi bin Mohd Shafri, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Siti Khairuniza Binti Bejo, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

ROBIAH BINTI YUNUS, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date :

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Name and Matric No. : Mohammed Oludare Idrees GS41930

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Signature: ____

Name of Chairman of Supervisory Committee: Professor Dr. Biswajeet Pradhan

Signature: ____

Name of Member of Supervisory Committee: Associate Professor Dr. Helmi Zulhaidi bin Mohd Shafri

Signature: ____

Name of Member of Supervisory Committee: Associate Professor Dr. Siti Khairuniza Binti Bejo

TABLE OF CONTENTS

				Page
ABSTRACT				i
ABSTRAK				iii
ACKNOWLEDGEMENTS				v
APPROVAL				vi
DECLERATION				viii
LIST OF TABLES				xiii
LIST OF FIGURES				xiv
LIST OF ABBREVIATIONS				xvii
CHAPTER				
1	**INTRODUCTION**			1
	1.1	General		1
	1.2	Problem Statement		3
	1.3	Motivation behind this reserach		5
	1.4	Research Objectives		6
	1.5	Research questions		7
	1.6	Scope of the Study		7
	1.7	Thesis Organization		7
2	**LITERATURE REVIEW**			9
	2.1	Introduction		9
	2.2	Cave, development and importance		9
	2.3	Evolution of 3D cave surveying with TLS		11
	2.4	Terrestrial laser scanning technology		16
	2.5	3D Cave scanning methodological developments and workflow		22
		2.5.1	Fieldwork: Planning and data collection	22
			2.5.1.1 Planning	22
			2.5.1.2 Data collection	23
		2.5.2	Data processing	25
			2.5.2.1 Scan registration and filtering	25
			2.5.2.2 3D Meshing	26
			2.5.2.3 Post-Processing	27
	2.6	Point clouds processing software packages		28
	2.7	Applications of 3D cave scanning in cave		33
		2.7.1	Archaeology	33
		2.7.2	Geomorphology	34
		2.7.3	Ice surface morphology change	34
		2.7.4	Ecology	35
		2.7.5	Palaeoclimatology and paleontology	35
		2.7.6	Passage stability/Hazard	35
		2.7.7	Visualization and education	36

	2.8	Advances in method, hard/software and computing over the decade	36
		2.8.1 Progress in sensor technology	37
		2.8.2 Advances in computing efficiency	38
		2.8.3 Software capability	38
		2.8.4 Future outlook	39
	2.9	The Edible Bird-Nest swiftlets of Gomantong cave	39
	2.10	Summary	42
3	**MATERIALS AND METHODOLOGY**		43
	3.1	Introduction	43
	3.2	Overall methodology	43
	3.3	Geological setting and study area	45
	3.4	Survey design, field campaign and data processing	46
		3.4.1 Terrestrial laser scanning survey	46
		3.4.2 Point cloud processing	48
		3.4.3 Output of laser scanning products	48
	3.5	Ensemble optimization process	49
		3.5.1 The hybrid optimization procedure	50
		3.5.2 Taguchi method	51
		3.5.3 Objective Function	52
		3.5.4 Robust Hybrid optimization strategy	53
	3.6	Segmentation and classification	56
		3.6.1 Validation	58
		3.6.2 Accuracy assessment	58
	3.7	Reliability testing	59
		3.7.1 Estimating overall effects	60
		3.7.2 Testing for heterogeneity	61
		3.7.3 Transferability assessment	61
	3.8	Surface reconstruction and geomorphology	62
		3.8.1 Definition of macro- and micro-geomorphology	63
		3.8.2 3D meshing	63
		3.8.3 Measurement of geologic rock structure	65
		3.8.3.1 Automatic extraction of planar facets	66
		3.8.4 Predicting direction of potential passage deformation	66
	3.9	3D Texture modelling and micro-morphologic feature identification	67
	3.10	Summary	68
4	**RESULTS AND DISCUSSION**		69
	4.1	Introduction	69
	4.2	Ensemble model test and validation results	69
		4.2.1 Classification results	72
		4.2.1.1 Test result	72
		4.2.1.2 Validation result	73
		4.2.1.3 Detection accuracy	75
		4.2.1.4 Reliability evaluation outcome	76
	4.3	Model transferability assessment	80

4.3.1 4.3.1 Model comparison with existing approach 83
4.4 3D mesh model/geomorphology of cave passage network 83
4.4.1 Cave morphometry and sectional drawings 86
4.4.2 Planar facets 88
4.4.3 Influence of rock deformation on cave passage development 91
4.4.4 Direction of potential passage development/failure 93
4.5 Virtual 3D model and geovisualization 94
4.5.1 Description of micro-morphological features 97
4.5.2 Cave art documentation 99
4.6 Summary 101

5 CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORKS 102
5.1 Introduction 102
5.2 General conclusions 102
5.3 Specific conclusions 103
5.4 Limitation of the study and recommendations for future research 104

REFERENCES 106
APPENDICES 120
BIODATA OF STUDENT 122
LIST OF PUBLICATIONS 123

LIST OF TABLES

Table		Page
2.1	TLS systems discussed and their basic properties with respect to cave surveys	21
2.2	Point cloud processing software packages	30
3.1	Technical specifications of FARO Focus3D terrestrial laser scanner	47
3.2	Definition of segmentation factors, levels and their variables	54
3.3	Design of experiment (DOE) with Taguchi orthogonal array L25	55
3.4	Comparison of ROC curves	60
4.1	Combined orthogonal array and the computed POF	70
4.2	Response table for signal to noise (S/N) ratio	71
4.3	Classification accuracy: Area under the ROC curve with associated performance measures	76
4.4	Estimated overall effects and test for heterogeneity	78
4.5	Area under the ROC curves with associated performance measures for accuracy and transferability assessment	82
4.6	Summary of basic geometric properties of the model	87
4.7	Summary of planes extracted and their mean dip, dip direction and root mean square	91

LIST OF FIGURES

Figure		Page
1.1	Photograph of the entrance section of the lower cave (Simud Hitam) taken during the laser scanning expedition	6
2.1	Gray scale intensity image of entrance section of Simud Hitam (Gomantong Cave) in north Borneo, Malaysia	17
2.2	Left - FARO Focus3D set up in October 2012 by Drs. Buchroithner and Pradhan (standing) and the two scanner operators in the Niah cave, Borneo. Right - Scanning with Riegl LMS Z420i at a rock pulpit in the Ramsau Dome, Dachstein South- face Cave, Styria, Austria, numbers 1-4 indicate the component parts: scanner, tripod, backup power pack and laptop (Source: Buchroithner et al., 2009 p.333)	24
2.3	3D point cloud of the entrance of Simud Hitam (Black cave) in Gomantong Hill, North-eastern Borneo, Malaysia (Source: McFarlane et al., 2013 p.317)	25
2.4	3D model of the Gomantong cave, Sabah, Malaysia taken from the animated video (Producer: Lundberg and McFarlane., 2012)	27
2.5	Color point cloud image of Skoteino Cave looking from the back toward the entrance; advance visualization allows stratigraphy within the limestone bedrock to be clearly denoted in the cave walls (Source: Tyree et al., 2014 p.187)	33
2.6	White-Nest swiftlet birds making their nests on the wall of the cave in preparation for egg laying	40
3.1	Overall methodological workflow	44
3.2	Location of Gomantong cave in (a) Borneo Island, (b) ASTER-GDEM of the state of Sabah (Malaysia Borneo) and (c) Google Earth image of Gomantong Forest Reserve with the hill at the centre	45
3.3	Hybrid optimization process using ensemble model to detect and count bird-nest	51
3.4	Segmentation process (top) raw laser intensity image showing swiftlet bird-nest (middle) multi-resolution and (bottom) spectral difference	57

3.5 3D visualization of the image scene for (A) lower cave (Simud Hitam) and (B) upper cave (Simud Puteh) 62

3.6 3D seamless point cloud of (a) the 7th point sampling of the 99 scans merged in CloudCompare and (b) plan view of the 5cm spatially sampled point cloud – height range in colour 64

4.1 Graph of the POF against experiment – the numbers above the curve is the level combination for each experiment 70

4.2 Mean effects plot for S/N ratios (Larger is better) 71

4.3 (a) Laser intensity image subset and (b) detected bird overlay on the image 73

4.4 TLS intensity image scene used for developing and testing the method (Top) with sections of the rectangular boxes A, B and C showing clearly the detected nests in red dots on the image for the three sections in that order 74

4.5 ROC curves classification analysis with brightness value (left) and brightness and area indices (right) 75

4.6 Comparison of area under the ROC curves of the six experiments 77

4.7 Area under the ROC curve of the six experimental trials at 95% confidence interval and the overall effects. The horizontal lines show the coverage of the confidence interval with square markers that vary in size according to the weights assigned 78

4.8 Six images used for validating the method showing the detected bird-nests in red dots 80

4.9 Optimized segmentation output of the images taken from Simud Hitam (lower cave) - left and Simud Putih (upper cave) – right. (A) Roosting swiftlet birds, (B) Roosting wrinkle-lipped bats (C & D) are the output of the segmentation, and (E & F) collapse of over-segmented cave wall after spectral segmentation was applied 81

4.10 ROC curves classification analysis for the lower cave (left) and upper cave (right) 82

4.11 3D model of the upper level cave (Simud Putih) produced in MesLab with ≈ 28.3 million points at octree depth of 10 84

4.12 Graphic description of the cave cavities (a) main chamber viewed W-E, (b) the horn-shaped entry passage viewed W-E, (c) secondary chamber where shaft 1(d) and shaft 2 (e) are connected, (f) main hall viewed from N-E to S-W at the centre of the hall, and (g) shaft 3 viewed towards the north direction 85

4.13 Side and cross sectional view highlighting passage outline of (a) entry channel (b) chamber (c) main hall (d) Shaft 2 (e) Shaft 1 and (f) Shaft 3 86

4.14 Normal oriented point cloud of the main hall (left) and extracted facets (right) 88

4.15 Stereogram of facets produced in CloudCompare. Label 1- 6 indicate plot of facets of the respective cave passage section (Entry passage, Chamber, Hall, Shaft 1, Shaft 2 and Shaft 3) 90

4.16 Mean dip/dip direction plotted as planes on Stereonet – Plane identity number indicates the passage section the plane represents while the background density plot is the poles (dip/dip direction) of the whole cave exported from FACETS as CSV file 92

4.17 Bi-directional data distribution Rose diagram of cave passage sections 94

4.18 Intensity-based texture model of Simud Puteh – topmost plate shows (a) the main entrance viewed from the base of the collapse sinkhole and (b) E-W direction towards the hall; plate (c) is the chamber viewed W-E, (d) Shaft 1 viewing the entrance from inside, (e) main hall viewed to the southern end, (f) Shaft 2 viewed northward, and the last plate views Shaft 3 from the hall where the passage opens to it, and (g) a view within the shaft 96

4.19 Rock surfaces (a) daylight opening in the roof (b) cliff (c) fault and fractured wall, and (d) semi-circular wall pillar (PL), including stalactite (STT) and stalagmite (STM) 98

4.20 Cave roof morphologies (a) scallops (b) ceiling flush dome (c) hanging rocks and fractures (d) ceiling pockets and bell-hole (e) ceiling aven of about 9m in diameter and 5m deep into the roof and (f) seepage 99

4.21 Cave arts on the wall - (a) paintings in Shaft 1 (b, c) picture of goat head and painting in Shaft 3 and (d) cave engraving in the Chamber, (e, f) cave inscriptions in entry passage 100

LIST OF ABBREVIATIONS

2D	Two-dimension
3D	Three-dimension
ALS	Autoscanning laser system
ASCII	American standard code for information interchange
AUC	Area under the ROC curve
CAD	Computer aided design
CAM	Computer aided manufacturing
CI	Confidence interval
DEM	Digital elevation model
DOE	Design of experiments
DT	Delaunay triangulation
EBN	Edible birds' nest
ETP	Economic transformation programme
GIS	Geographic information system
GNI	Gross national income
GPS	Global positioning system
HDR	High density resolution
HDS	High density scanning
ICP	Iterative closest points
IMU	inertia measurement unit
Kd-Tree	K-dimensional tree
LiDAR	Light detection and ranging
LMS	laser measurement system
OBIA	Object-based image analysis

POF	Plataeu objective function
PS	Phase shift
RGB	Red, green and blue
RMSE	Root mean square error
ROC	Reciever operating characteristics
S/N	Signal-to-noise
SD-card	Secure Digital Card
TIN	Triangulated irregular network
TLS	Terrestrial laser scanning
TOF	Time of flight
USFWS	U.S. Fish and Wildlife Service
Z+F	Zoller+Frohlich

CHAPTER 1

INTRODUCTION

1.1 General

Perhaps accidental but fortunate for the largest island in Asia, North Borneo Island, that a number of great caves whose human use date back to the 13th century are the choice of swiftlet birds to nest in large colonies. Chinese merchants visited North Borneo caves during the Ming Dynasty (1368 to1634) dealing in swift birds' nests (Dunkley, 2004). This early visit has been the bond to the well-developed trading network since early 15th century till present-day multi-million dollar edible birds' nest (EBN) industry.

The first reference to the trade is cited in connection with the visit of the Chinese Admiral, Cheng Ho, during his expedition to the Malay Archipelago in 1406 (Chasen, 1931; McAfee, 2011; Price, 2007). The unfortunate experience of Admiral Cheng and his crew during their turbulent voyage led to the discovery of edible swiftlet birds' nest in a cave where they rest for some days before continuing their journey. In a related development, an Arab missionary Machdon, Alawlia, was reported to have visited Sabah Coast with trading vessel two years later (Price, 2007). These two historic visits hint on the centurial trading network that has been in existence ever since and which has continue to flourish untill this present time.

Today, several thousands to millions of swiftlets birds still nests in a number of caves in Northern Borneo, contributing significantly to the regional economy and, at the same time, providing stable income to the local communities. Most prominent among the caves is the Gomantong cave famous for its long history as the single leading source of edible swiftlet birds' nest in South East Asia (Abdullah et al., 2005; Lundberg and McFarlane, 2012; McFarlane et al., 2015b; Price, 2014). Although, there is no reference to the exact date in which Gomantong cave was discovered, early documents compiled by the Chattered Company was cited to have traced its ownership to a man called Pengeran di Gadon Samah (Chasen, 1931). However, a contrary but informative anonymous article published on page 3 of the *British North Borneo Herald* of 11th March, 1884, claimed Pengeran Samah's grandfather was the first to control the valuable birds' nest caves. The link to these two generations of the same lineage obviously indicates that possession has passed on from one generation to another.

Over the past century, there has been a dramatic increase in studies concerning Gomantong cave. This may not be far from the realization of the fact that swiftlet birds' nests have become one of Malaysia's main agricultural export commodities of very high market demands from Asian countries such as Hong Kong, China, Taiwan, Macau and Singapore (McAfee, 2011). In the Chinese tradition, it is believed that birds' nests is an important food sources for health with natural healing potentials efficacious for curing several ailments that include among others: tuberculosis, strengthening the immune system, speeding recovery from illness and surgery, increasing energy, increasing libido, improving concentration, accentuate complexion, etc. (Lundberg and McFarlane, 2012; Ng, 2012; Noad, 2001). This traditional epitome has consequently created an economic mainstream for the nation that makes it an obligation for the government to assume a more active role in ensuring effective and efficient management strategies.

Highlighting the economic importance of EBN industry, Lim et al. (2012) mentioned that the state earned well over US$4.2 million through export of 8,876 kilogram edible birds' nest in 2009. Likewise *Economic Transformation Programme* (ETP) report of 2014 put export of edible birds' nest products for year 2014 at 145 tonnes while 200 tonnes is targeted for 2015. In another high-level national agenda to maximize economic prosperity, the Malaysian government have discovered a niche in swiftlet farming far beyond the local earnings. As projected in the ETP's annual report of 2014, Malaysia planned to increase upstream production of edible birds' nest farming to yield Gross National Income (GNI) of US$4,541.2 million and to create 20,800 jobs by year 2020 (ETP, 2014). This bold move underlines the degree to which Gomantong cave which is the largest source of this valuable product in Sabah need to be approached with multi-faceted and integrative studies for informed management decisions.

Until lately, ecological research, especially species population census of the inhabitants of caves, has been largely stalled due to perpetual darkness, inaccessibility, and harsh environmental conditions of this unconventional ecosphere (Lundberg & McFarlane, 2012). Gomantong is one of the caves in north Borneo Island with large population of Black and White Nest swiftlet birds (*Aerodramus maximus* and *Aerodramus fuciphagus*) and wrinkle-lipped bats (*Chaerephon plicata*) sharing their dark home (Chasen, 1931). The cave provides naturally confined speleogenetic setting which supports stable microclimate that make them particularly attractive habitat for these species in large number. A total number of twelve species of insectivorous bats estimated to be between 600,000 - 2 million are identified in the cave (Abdullah et al., 2005; Kingston, 2010). Also, about 1.29 and 1.5 million population of black and white-nest swiftlet birds coexist along with the bats in their dark home (Lim et al., 2012; Tompkins, 1999).

The cave is constantly alive with swiftlet birds, bats, and other smaller creatures such as rats, insects, and other invertebrates. Bat and, to some extent, swiftlet droppings (guano) support the cave ecology and sustain the predator-prey relationship within the micro eco-climate (Abdullah et al., 2007; Price, 2014). Economically, the high commercial value of edible bird nests which are made entirely or partly of glutinous saliva containing soluble glyco-proteines and cellular elements has attracted pivotal socio-economic attention of both the indigenous people and the nation for centuries.

Furthermore, the cave is a popular destination that receives a large number of both local and foreign tourists that stream in to experience the thrilling swiftlet birds' nest harvesting, astounding bat swarm, and the cave powerhouse, guano (Kingston, 2010; Price, 2007). In spite of the centennial interaction of people with the cave and the apparent threat posed by incessant harvesting, it has not been possible to keep track of the swiftlets population in the cave until now due to absence of a practical counting method; neither is there a clear understanding of their preference for choosing roosting location with respect to the cave's 3D geometry.

Interestingly however, the growing use of high resolution terrestrial laser scanning (TLS) in caves has recently triggered a new perspective in cave studies on different fronts including biospeleology, particularly roosting bats and birds. This field of enquiry, pioneered by Azmy et al. (2012) and McFarlane et al. (2015b), demonstrates the potentiality of TLS datasets for population surveys as well as understanding the relationship between roosting and the cave morphology. Although the methods adopted by these researchers are inventive; the use of only the intensity information in the former, and the need for full resolution scan in the latter, limits the application of their approaches. Thus, in the phase of rising concern for these ecologically endangered species in Gomantong cave and the potential loss of the cave itself to post-speleogenetic modifications, this study employs TLS data to develop an efficient method to detect and count swiftlet bird-nests and to explore the state of the cave passage morphologies from three-dimensional (3D) model.

1.2 Problem Statement

Scientific studies in Gomantong cave can be traced back to the late 19th century. For example, Price (2007) mentioned that in 1889, J. H. Allard of the China Borneo Company investigated Gomantong cave for phosphate deposits as source of fertilizer while Mr S. G. Holmes is also mentioned as the man who produced the first rough sketch of the Caves. However, these investigations were carried out for the government in the context of birds' nest industry for internal use. The report of Chasen (1931) was the first to expose the scientific resourcefulness of Gomantong cave systems. He covered in detail a range of issues: history, ownership, economic importance, cave structure vis-a-vis the forest reserve, swiftlets behaviour and reproduction, nest structure, harvesting, and management issues. Afterwards, several other knowledge-centred studies have emerged, most of which have primarily focused on the species and behavior of the swiftlet birds and bats in the cave (e.g. Abdullah et al., 2005; Abdullah et al., 2007; Chasen, 1931; Hobbs, 2004; Lim et al., 2012; McFarlane et al., 2015b; Price, 2007; Tompkins and Clayton, 1999; Tompkins, 1999), However, no rigorous study has been carried to estimate the swiftlet colony.

Several techniques are available for bird census and survey in the terrestrial environment (Froidevaux et al., 2015; Gregory et al., 2004). These techniques, however, are not applicable for population survey of cave roosting birds because of the complexity of the cave structure and poor visibility (Lerma et al., 2010; WWF, 2004). There has been a long tradition of population surveys of cave roosting bats, usually employing either direct roost counts (Azmy et al., 2012; McFarlane et al., 2015b; USFWS, 2015) or emergence counts (Hallam et al., 2010; Hristov et al., 2008; Hristov et al., 2010; Kunz et al., 2009; McFarlane et al., 2015a). Direct roost counts record single individual bats while larger clusters are spatially sampled by multiplying roost area in the cave ceiling by parking density. However, the use of this method had been widely criticized for intrusiveness, rigor and difficulty in implementation (Hristov et al., 2010; Kunz et al., 2009). In recent years, the use of photography aided with headlamp and/or flashlight have also been incorporated to expedite the process of direct roost counting and to improve the accuracy of the result (USFWS, 2015). Contrary to the direct roost count, the indirect method utilizes the traditional evening emergence counts at cave entrances, often aided by optical-mechanical devices such as infrared camera, radar systems and acoustic bat detectors, to record the number of bats exiting the cave. But unfortunately, emergence count is possible only in the daylight time or at crepuscular period (Azmy et al., 2012; McFarlane et al., 2015a). While the direct and emergence count methods have been successful for bat population survey, they are not applicable for estimating swiftlets population because swifts do not have unique roosting behavior, and defined time and pattern of movement like bat.

Therefore, population of swiftlet birds has been traditionally observed through the nest count as an indirect approach to determining colony size. This approach was proposed by (Vijayan and Sankaran, 2000) following extensive study towards action plan for the conservation of the endemic birds of the Andaman and Nicobar Islands in India. A recent study with similar objective used the nest count method to estimate swift population in Taytay, Palawan province in Phillipines (Edwin and Glenda, 2014). Swiftlets build their edible nests during the breeding season, usually from December to June in preparation for egg laying and are harvested at specific period within this time frame. So, nest count estimate are usually based on nest yield. And average annual nest collection estimate inferred total estimated population size, arithmetically multiplying nest counts by a breeding pair of swiftlets while variation in population can be determined through change in nest yield data between two periods.

In Gomantong, there are a lot of pressures threatening the survival of swiftlet birds and their habitat (the caves). Studies across Southeast Asia have reported that nest harvesting affects the swifts' breeding success (Gregory et al., 2004; Hobbs, 2004; Ramji et al., 2013; Tompkins, 1999), and consequently, reduction in population and harvest yield. Monitoring population of swifts in the cave will become valuable information, not only for scientific study but, for conservation planning and resource management. The existing nest counting technique based on nest yield count is not effective because:

1. It is an obvious fact that many nests are not collected because they are not accessible due to bad lighting and many are built in positions that defies even the boldest of the climbers.
2. In Gomantong cave, there is room for both birds and bats, and there is still plenty of unoccupied space. It is still difficult to account for the birds' choice of sites within the cave systems without reliable data and accurate 3D map of the cave.

3. There are reports of drastic decline in the swiftlet colonies in the cave; however, to what extent these colonies decrease (or possibly increase) cannot yet be ascertained due to the problem stated above.
4. Lack of accurate 3D map has limited complete understanding of the structure and geomorphology of the cave passages and how their development is influenced by the geologic rock structure. No clear understanding of the interplay of zoogenic, human and geologic interference in the modification of the cave passages despite reports that large sections of the caves are not occupied by either bats or birds (Chasen, 1931; Lundberg & McFarlane, 2012).
5. Recent study by Lundberg and McFarlane (2012) reveals that the cave passage of Simud Hitam has been extremely modified by biogenic corrosion. It is unclear to what degree post-speleogenetic deformation has affected the cave passages and how much of the passages still retain their original phreatic tube formation.

1.3 Motivation behind this reserach

Gomantong cave has a time-honoured cultural and historical vibrancy having been known as the largest cave in South East Asia. Awareness of the wealth of information conveyed in laser scanning data and the significant role high resolution 3D documentation can play in deepening inclusive understanding of cave, motivates this research. Gomantong cave is selected for this studies for two main reasons: (1) the cave, with its large colonies of the swiftlet birds, is the more popular site for birds' nest collection than any other cave in Malaysia; (2) due to its interesting geomorphological conundrum such as (a) some of the passages are very large, as much as 60m high, often breaking to the hill surface – and quite disproportionate to the hydrology of the hill, (b) there appears to be two quite distinct passage morphologies – i) normal phreatic tubes of rounded or oval cross-section with current scallops lining the walls indicative of classic speleogenesis under flooded conditions ii) distinctly non-normal very tall passages with sheer vertical walls lined with extraordinary, large flutes (Figure 1.1).

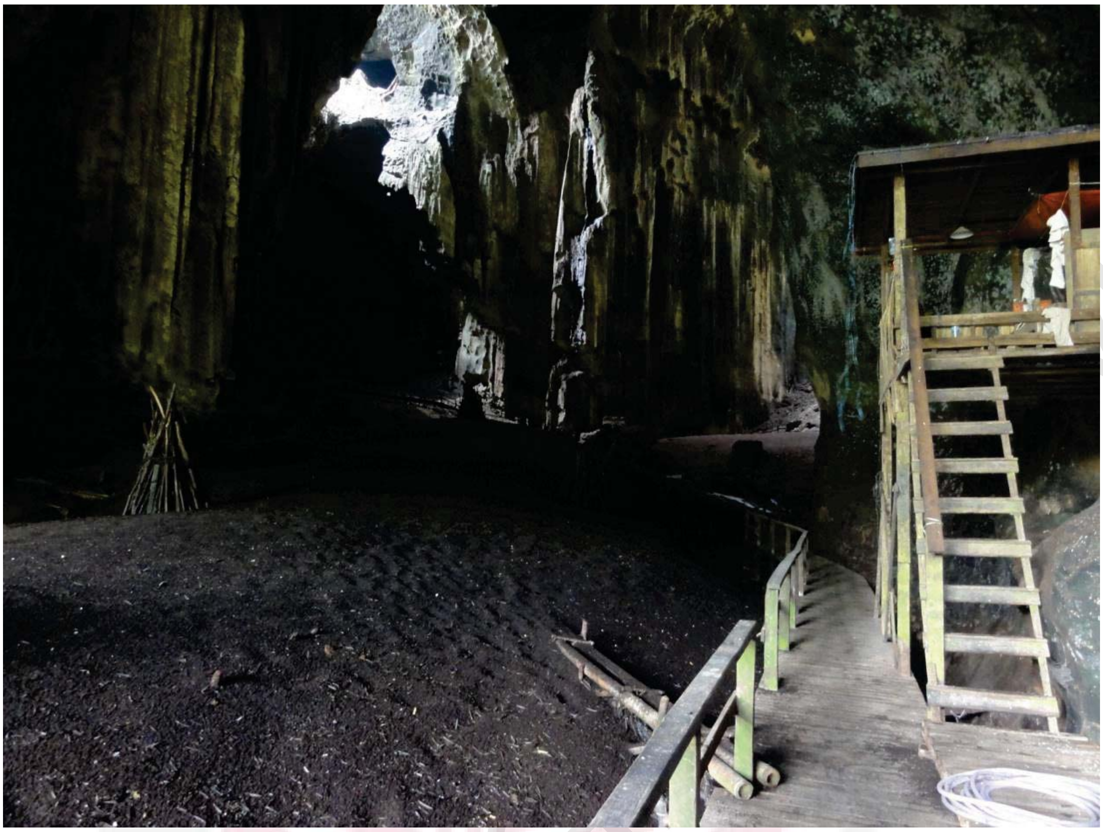

Figure 1.1 : Photograph of the entrance section of the lower cave (Simud Hitam) taken during the laser scanning expedition.

Here, this thesis proposes a novel technique to count bird-nests in the cave by employing remote sensing image processing approach with high resolution terrestrial laser scanning intensity image using integrative spatial and statistical optimization synergy. This perspective is interesting because it takes the conventional image analysis for feature extraction on the terrain surface to the underground environment. Another point of view is the proposition that 3D texture model using full scan resolution and the intensity value in place of the RGB colour images can offer an excellent platform for pseudo-realistic visualization and micro-geomorphological investigations at high level of accuracy. This is a paradigm shift from the usual 3D mesh widely used for similar applications.

1.4 Research Objectives

The main objective of this study is to develop an ensemble modeling approach for automatic counting of cave roosting birds using TLS intensity image. The method takes into consideration the basic elements of simplicity, repeatability, comprehensiveness and fitness for purpose. In addition, a new approach to 3D documentation of cave using texture model based on laser intensity return is also proposed.

The following are the specific objectives of the thesis:

1. To develop and test an ensemble model to detect and count bird-nests from TLS intensity image and assess its transferability in Simud Hitam.
2. To model the cave in three-dimensional (3D) geometric space at low and high resolution scales.
3. To characterize the macro and micro-geomorphological features of the cave channels from the 3D models.

1.5 Research questions

This thesis comprehensively addresses the following research questions:

1. Can TLS data provide accurate and economical means of estimating colony size of bird-nest (and bats) in Gomantong cave?
2. How much of the cave system retains its relict original phreatic tube morphology and how much has been biogenically augmented and where within the cave?
3. Is zoogenic induced processes only the factor responsible for passage deformation or are there other factors?
4. What is the wall and ceiling morphology of those parts that are not accessible?
5. Is there a Pattern to the location of roosting bats and swiftlet birds?
6. Is the cave prone to potential rock failure hazards?
7. How much of the rock is in fact cavity?
8. To what degree does the geologic rock structure controls the development of the passage networks?

1.6 Scope of the Study

This study aims only to explore the upper cave (Simud Puteh) of the Gomantong cave exclusively from terrestrial laser scanning survey expedition carried out in the cave in 2014. The reason for this is that there is limited information about that section of the cave due to access difficulty. The method developed for detecting and counting birds was applied in the upper cave and its applicability tested in the lower cave. The research is entirely a data-driven exploration from different professional application point of view which include ecology, geomatic, geomorphology, geology, and archaeology. However, the proposed methodology for both the bird population censusing and pseudo-reality 3D documentation of cave may be supplemented in other areas.

1.7 Thesis Organization

This thesis is organized into five chapters. Chapter One provides detail background of the research including the problem statement, objectives, motivations behind the study. Also discussed in the chapter is the research questions, scope and, finally, the overall structure of the thesis. In Chapter Two, detail literature review of the journey of modern cave surveying with terrestrial laser scanning is presented. The chapter focuses on all aspects: instrumentation and the theoretical foundation, scanning procedure and point cloud processing. Furthermore, the various applications of laser scanning products, advances in sensor development, software capabilities and computing efficiency over the last decade are presented.

Chapter Three presents in detail the general methodology after a brief description of the study site. At the foremost level is the laser scanning survey of the cave and point cloud processing from which laser intensity images and 3D point datasets were generated. This was followed by description of specific methods employed to achieve individual objectives such as the integration Taguchi-Objective Function optimization strategy in developing an ensemble modeling approach for bird counting and its dependability, multi-resolution scale 3D modeling and geomorphological analysis. Based on the sequence of the methodology presented in the previous chapter, Chapter Four focuses on the results and discussion. The results of the modeling approach, detection accuracy, reliability and transferability are explained with supporting tables and figures. Similarly, the low and high resolution 3D models and the different applications including geovisualization, passage structural, morphometry and geomorphological analysis are presented and discussed. Also presented in the chapter is the potential of textured 3D model for cave art identification and documentation. Lastly, Chapter Five provides the overall conclusion of the study and recommendation for further studies.

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