



**UNIVERSITY OF
CANBERRA**

AUSTRALIA'S CAPITAL UNIVERSITY

*Automated visibility map from colonoscopy video to support clinical
diagnosis and improve the quality of colonoscopy*

Mohammad Ali Armin

A THESIS SUBMITTED FOR THE DEGREE OF DOCTOR OF PHILOSOPHY OF

THE UNIVERSITY OF CANBERRA

FACULTY OF EDUCATION SCIENCE TECHNOLOGY AND MATHEMATICS

NOVEMBER 2016

I DEDICATE THIS TO MY PARENTS WHO ARE THE LIGHT OF MY LIFE.

Abstract

Colorectal cancer is one of the leading cause of cancer related deaths in the world. In 2012, it was reported to have claimed more than 694,000 lives worldwide [1], [2]. When diagnosed early, survival from cancerous polyps can increase up to 90% [1]. Current reports estimate that one in 12 Australian males will develop colorectal cancer within their lifetime, one of the highest rates in the world [1]. Among screening methods, optical colonoscopy is widely used to diagnose and remove cancerous polyps. Although optical colonoscopy is an effective procedure for diagnosing colorectal cancer, there are many factors that affect the quality of this intervention [3]. Inspecting the whole colon surface in order to detect polyps and other lesions is challenging because haustral folds can hide lesions, the organ might deform, visibility can be reduced due to dirty lens, and also because challenges in operating the colonoscope could result in not visualising all the colon surface. An undesirable consequence is missing cancerous lesions, up to 33% according to recent publications [4], [5].

The aim of this research project is to enhance the quality of colon inspection by improving the quality and extent of the visual inspection of the internal colon surface. We developed an assistive technology to provide a panoramic view of internal colon surface (visibility map) from a colonoscopy video. A visibility map could provide feedback to clinicians about the quality of the intervention (potentially in real time), for example by increasing their awareness of uncovered areas by the video. It could also be beneficial for following up patients and tracking lesions over multiple exams. Visibility map could also be a core technology for training junior clinicians.

Challenges to generate visibility maps include: (i) Colonoscopy videos comprises many uninformative frames (frame with no technical or clinical information); (ii) the colon is a flexible tubular organ that makes navigation challenging, not only for clinicians, but also for computer vision algorithms; (iii) the structure of the colon is complex with many haustral folds requiring complicated modelling.

Our novel framework comprises four main phases: (i) detect uninformative frames from motion and colour features, (ii) compute camera parameters including intrinsic and extrinsic one using epipolar geometry analysis, (iii) model the colon and project the model into colonoscopy frames using camera parameters, and (iv) unroll and stitch the frames, correcting camera parameters, and generate a visibility map. We leveraged the existing state of art CSIRO realistic simulator by generating test examples and validation experiments where ground truth could be known from the simulator. Our results showed that this method could detect uncovered areas and help clinicians to identify them. Although more work is required, the wide spread use of this technology could help reducing the miss rate of polyps, which will increase the quality of colonoscopy procedure and ultimately save lives.

Acknowledgments

PhD is a long journey when you are alone, but I have done this with the support of the knowledgeable, wise, and experienced scholars. I would like to express my deep gratitude to A/Prof. Olivier Salvado and A/Prof. Girija Chetty, my supervisors at Commonwealth Scientific Industrial and Research Organisation (CSIRO) in Brisbane and University of Canberra (UC), for their continuous support toward my PhD study and research, their patience, enthusiasm, encouragement, and immense knowledge. Their aspiring guidance helped me in all the time of research and writing of this thesis. I could have never completed this thesis without their generous support.

I also would like to thank the rest of my supervisory panel, Professor Roland Goecke, A/Prof Cedric Dumas, and A/Prof Hans de Visser for their encouragement, and insightful comments. In addition, I would like to thank Dr Florian Grimpén for providing us with actual colonoscopy videos, and assisting us to analyse the outcomes of this research. David Conlan, the senior software engineer at the heart of colonoscopy simulation team is another person that I would like to deeply appreciate for his kind assistance with the simulator.

My grateful thanks also go to Professor Roland Goecke the research leader for the Information Technology & Engineering research program, and HCT Centre director at UC not only because he introduced the science of image processing and computer vision to me, but also because he generously supported my study. I also would like to appreciate the Dean Professor Geoffrey Riordan for his warm support, and my previous lecturers at the university of Canberra, especially A/Prof Dat Tran, A/Prof Masoud Mohamadian, and my friends A/Prof Sharon Kazemi and Prof Alan Forghani.

Furthermore, I would like to express my heartfelt gratitude to my parents and my dearest friends Amir Fazlollahi and Zahra Shahabi who inspired me through this research.

I also like to thank all e-health research centre members in Brisbane, who were supportive and inspired me through my PhD journey. I also would like to express my appreciation to the Research Student office, graduate research office, UC and CSIRO library for their support.

Last but not least, during this research my dearest uncle and two of my relatives passed away due to lung and colon cancer, so I would like to dedicate this achievement to them and all other patients, and I hope the application of this research can potentially save peoples' lives in future.

Table of Contents

ABSTRACT.....	III
FORM B.....	V
ACKNOWLEDGMENTS	VII
TABLE OF CONTENTS.....	IX
LIST OF FIGURES.....	XIII
LIST OF TABLES.....	XV
ABBREVIATIONS.....	XVII
KEY TERMS	XIX
CHAPTER 1 INTRODUCTION.....	1
1.1 INTRODUCTION.....	1
1.2 SIGNIFICANCE AND MOTIVATION	2
1.3 BACKGROUND	4
1.3.1 Colon anatomy.....	4
1.3.2 Colorectal cancer	5
1.3.3 Colorectal cancer diagnosis methods.....	7
1.3.4 Colonoscopy procedure	7
1.3.5 Colonoscope.....	8
1.4 MISSED POLYPS RATE IS A LIMITATION OF COLONOSCOPY	11
1.4.1 Polyps type and position.....	11
1.4.2 Clinicians' skill	12
1.4.3 Full colon inspection	12
1.5 CURRENT METHODS IN ASSISTING CLINICIANS TO IMPROVE THE QUALITY OF OPTICAL COLONOSCOPY.....	13
1.5.1 Medical approach	13
1.5.2 Technical approach.....	13
1.5.3 Quality metrics.....	14
1.5.4 Polyp detection	15
1.5.5 Uncovered areas detection.....	15
1.5.6 Summary of the currents quality metrics and assistive technologies for improving the quality of colonoscopy and our proposed method	17
1.6 RESEARCH QUESTIONS.....	18
1.7 THESIS CONTRIBUTIONS.....	19
1.8 PUBLICATIONS	20
1.9 THESIS OUTLINE	21

CHAPTER 2 CLASSIFICATION OF COLONOSCOPY FRAMES	23
2.1 INTRODUCTION, MOTIVATION AND CHAPTER OUTLINE	23
2.2 LITERATURE REVIEW AND RELATED WORK	24
2.2.1 Colonoscopy frames.....	24
2.2.2 Features used for endoscopy frame classification	25
2.2.3 Machine learning.....	28
2.2.4 Uninformative frame detection.....	30
2.2.5 Limitations of existing methods	31
2.3 PROPOSED METHOD	32
2.3.1 Feature detection.....	33
2.4 DATASET.....	37
2.5 EXPERIMENTAL EVALUATION	37
2.6 RESULTS	38
2.7 DISCUSSION AND FUTURE WORK	40
2.8 CONCLUSION	41
CHAPTER 3 CAMERA MOTION ESTIMATION FROM OPTICAL COLONOSCOPY.....	43
3.1 INTRODUCTION, MOTIVATION AND CHAPTER OUTLINE	43
3.2 LITERATURE REVIEW AND RELATED WORK	44
3.2.1 Computer vision based algorithm	44
3.2.2 Combination of methods	48
3.2.3 Limitations of camera motion estimation from colonoscopy videos	48
3.3 OVERVIEW OF THE PROPOSED METHOD.....	50
3.4 CAMERA MODELS AND CALIBRATION	51
3.4.1 Camera model.....	51
3.4.2 Camera calibration	57
3.5 MOTION FEATURE DETECTION AND TRACKING	59
3.5.1 KLT feature tracking and filtering.....	61
3.6 CAMERA MOTION ESTIMATION THROUGH EPIPOLAR GEOMETRY	62
3.6.2 Camera pose estimation and optimisation.....	65
3.6.3 Kalman filtering	66
3.7 DATASET.....	67
3.7.1 Simulated video	67
3.7.2 Actual colonoscopy video	68
3.8 EXPERIMENTS AND VALIDATION	68
3.9 LIMITATIONS	71
3.10 DISCUSSION	71
3.11 CONCLUSION AND FUTURE WORK	72

CHAPTER 4 UNCOVERED AREA DETECTION AND CAMERA LOCATION CORRECTION	73
4.1 INTRODUCTION, MOTIVATION AND CHAPTER OUTLINE	73
4.2 LITERATURE REVIEW AND RELATED WORK	75
4.2.1 A panoramic image from internal organ	75
4.2.2 Camera motion correction from band image registration	83
4.2.3 Current gap in generating a visibility map from internal colon surface and drift in camera motion estimation	84
4.3 OVERVIEW OF THE PROPOSED METHOD.....	85
4.4 CAMERA MOTION ESTIMATION	86
4.5 UNROLL COLONOSCOPY IMAGE AND UPDATE CAMERA LOCATION.....	86
4.5.1 Model colon as a cylinder	87
4.5.2 Project colon model into image.....	88
4.5.3 Band image extraction	91
4.5.4 Band image registration	91
4.5.5 Camera location correction through band image registration	92
4.6 VISIBILITY MAP GENERATION AND UNCOVERED AREA DETECTION	93
4.7 DATASET.....	94
4.7.1 Simulated video	94
4.7.2 Actual colonoscopy video	95
4.8 EXPERIMENTS AND VALIDATION	95
4.8.1 Visibility map from realistic simulated videos.....	95
4.8.2 Application to actual colonoscopy video.....	97
4.8.3 Camera motion correction.....	99
4.9 LIMITATIONS	101
4.10 DISCUSSION AND CONCLUSION	102
CHAPTER 5 SUMMARY AND FUTURE WORK.....	105
5.1 SUMMARY	105
5.2 RESULTS AND FUTURE WORK.....	106
BIBLIOGRAPHY.....	111

List of Figures

FIGURE 1 TWO SAMPLES OF VISIBILITY MAP.	3
FIGURE 2 COLON ANATOMY.....	4
FIGURE 3 DIFFERENT TYPE OF POLYPS IN COLON.....	5
FIGURE 4 MORTALITY IN AUSTRALIA FROM BOWEL CANCERS.....	6
FIGURE 5 RELATION BETWEEN STAGES OF DIAGNOSING COLON CANCER AND THE CHANCE OF SURVIVING.....	6
FIGURE 6 COLONOSCOPY CAMERA AND INTERNAL VIEW OF THE COLON INCLUDING ABNORMALITIES.....	8
FIGURE 7 OLYMPUS COLONOSCOPE (190 HD), IMAGES ARE BORROWED FROM.....	9
FIGURE 8 THE CSIRO COLONOSCOPY SIMULATOR.....	10
FIGURE 9 ACTUAL COLONOSCOPY, AND SIMULATED FRAME FROM THE CSIRO COLONOSCOPY SIMULATOR.....	10
FIGURE 10 AN EXAMPLE OF A 3D MESH CONSTRUCTED WITH A SUCCESSION OF CHAMBERS.....	11
FIGURE 11 POTENTIAL AREAS WHICH HAVE NOT BEEN OBSERVED (UA).....	16
FIGURE 12 THE MAIN PROCESSING STEPS OF OUR FRAMEWORK TO GENERATE A VISIBILITY MAP.....	21
FIGURE 13 INFORMATIVE, AND UNINFORMATIVE FRAMES.....	25
FIGURE 14 THE SCHEMATIC OF THE PROPOSED METHOD FOR CLASSIFICATION OF COLONOSCOPY FRAMES.....	33
FIGURE 15 NUMBER OF FEATURE DETECTED BY THE KANADE LUCAS TOMASI (KLT).....	34
FIGURE 16 THE STD OF HUE, SATURATION, AND VALUE FOR SEVERAL INFORMATIVE AND UNINFORMATIVE FRAMES.....	35
FIGURE 17 PERCENTAGES-OF-EDGE-PIXEL TO ALL PIXELS FOR DIFFERENT TYPES OF COLONOSCOPY FRAMES.....	36
FIGURE 18 THE PROPOSED MOTION, EDGE FEATURES COMPUTED ON A REPRESENTATIVE INFORMATIVE FRAME.....	39
FIGURE 19 THE PROPOSED MOTION, AND EDGE FEATURES COMPUTED ON A REPRESENTATIVE UNINFORMATIVE FRAME.....	39
FIGURE 20 AN OBJECT OR SCENE FIRST TRANSFERRED TO THE CAMERA COORDINATE.....	45
FIGURE 21 OUR PROPOSED CAMERA MOTION ESTIMATION FRAMEWORK.....	51
FIGURE 22 A 3D OBJECT OR SCENE CAN BE PROJECTED INTO IMAGE PLANE.....	52
FIGURE 23 GENERAL PERSPECTIVE CAMERA MODEL.....	53
FIGURE 24 SIDE VIEW OF CAMERA FRUSTUM (LEFT) AND COMPUTER GRAPHICS CAMERA (RIGHT).....	53
FIGURE 25 THE SCHEMATIC OF FISHEYE LENS CAMERA MODEL.....	56
FIGURE 26 ACTUAL COLONOSCOPY IMAGE DISTORTION CORRECTION.....	57
FIGURE 27 CAMERA CALIBRATION BY SCARAMUZZA ET AL. [243] APPROACH.....	58
FIGURE 28 A SAMPLE OF APPLICATION COMMON MOTION FEATURE DETECTOR IN OUR COLONOSCOPY FRAMES.....	60
FIGURE 29 A COMPARISON BETWEEN SOME OF COMMON FEATURE EXTRACTOR USED IN ENDOSCOPY IMAGES.....	60
FIGURE 30 THE VECTORS ARE KLT FEATURES AFTER REMOVING THE UNRELIABLE FEATURES USING RANSAC PROCEDURE.....	62
FIGURE 31 CAMERA MOTION MODEL.....	63
FIGURE 32 FROM IMAGE IN SATURATION COLOUR CHANNEL FEATURES WERE DETECTED AND TRACKED BY KLT.....	66
FIGURE 33 TWO EXAMPLES OF SIMULATED COLON USED IN OUR EXPERIMENTS.....	68
FIGURE 34 THE ROOT MEAN SQUARE (RMS) ERROR OF CAMERA MOTION.....	69
FIGURE 35 THE TRAVELLED DISTANCE BY THE CAMERA WHEN IT TRAVELLED THE WHOLE COLON.....	70
FIGURE 36 OPTIMISED CAMERA PATH.....	70
FIGURE 37 UNCOVERED AREAS ARE SHOWN AS BLACK SPOTS IN THE VISIBILITY MAP.....	74
FIGURE 38 SOME OF THE BASIC SETS OF 2D IMAGE TRANSFORMATIONS.....	77
FIGURE 39 EXAMPLES OF PANORAMA VIEW OF MEDICAL IMAGES.....	79
FIGURE 40 EXAMPLES OF PANORAMA VIEW GENERATED FROM TUBULAR ORGANS.....	83

FIGURE 41 THE MAIN SCHEMATIC OF OUR PROPOSED METHOD TO GENERATE VISIBILITY MAP.	86
FIGURE 42 COLON MODELLED AS A CYLINDER.	87
FIGURE 43 3D RECONSTRUCTION OF A SEGMENT OF COLON.	88
FIGURE 44 PROJECTION OF CYLINDER INTO VIDEO FRAMES.	89
FIGURE 45 THE LEFT IMAGE IS AN ACTUAL COLONOSCOPY IMAGE BEFORE APPLYING OTSU METHOD.	90
FIGURE 46 PROFILE LINES REPRESENTING THE INTENSITY VALUE OF IMAGE.	90
FIGURE 47 THE FIRST ROW REPRESENTS THE FITTED CYLINDRICAL MODEL INTO THE COLON STRUCTURE.	91
FIGURE 48 SURF FEATURES WERE DETECTED AND MATCHED BETWEEN CONSECUTIVE BAND IMAGES.	92
FIGURE 49 SOME IMAGES CAPTURED WHEN CAMERA WAS MOVING INSIDE A COLON SEGMENT.	93
FIGURE 50 SIMULATED COLON, AND EXAMPLE OF VISIBILITY MAP.	94
FIGURE 51 VISIBILITY MAP GENERATED FROM A SEGMENT OF SIMULATED COLON.	96
FIGURE 52 A SAMPLE VISIBILITY MAP FROM A SEGMENT OF A REAL COLON.	98
FIGURE 53 THE VISIBILITY MAP FROM A SEGMENT OF COLON.	99
FIGURE 54 THE ESTIMATED CAMERA LOCATION IN Z DIRECTION WAS CORRECTED.	100
FIGURE 55 THE PERCENTAGE OF IMAGES WITH SIMILAR ERROR BEFORE AND AFTER CAMERA LOCATION.	100
FIGURE 56 THE GREEN CURVE INDICATES THE ESTIMATED CAMERA LOCATION IN Z DIRECTION.	101
FIGURE 57 MAPPING POLYPS TO VISIBILITY MAP.	107
FIGURE 58 ACTUAL COLON GEOMETRY AND CAMERA MOTION CAN BE ESTIMATED FROM SIMULATED FRAMES.	108
FIGURE 59 SUSPICIOUS HAUSTRAL FOLD DETECTED ON A REAL FRAME (LEFT), AND SIMULATED FRAMES (RIGHT).	109

List of Tables

TABLE 1 ESTIMATED INCIDENCE OF CANCER IN 2012 [1].	5
TABLE 2 COLONOSCOPIES (PUBLIC AND PRIVATE SECTOR) IN AUSTRALIA [38].	7
TABLE 3 CHARACTERISTIC OF POLYPS MISSED AT PROSPECTIVE COLONOSCOPY EVALUATION [20]	12
TABLE 4 FEATURES ESTIMATED FROM CO-OCCURANCE MATRICES.....	36
TABLE 5 DATASET USED IN OUR EXPERIMENT TO DETECT UNINFORMATIVE FRAMES.....	37
TABLE 6 THE PERFORMANCE OF DIFFERENT FEATURE DESCRIPTORS ON IDENTIFYING UNINFORMATIVE FRAMES.	40
TABLE 7 VIDEO SEGMENTS GENERATED BY CSIRO SIMULATOR FOR OUR EXPERIMENTS.	97
TABLE 8 ACTUAL COLONOSCOPY VIDEO SEGMENTS, AND UNCOVERED AREAS.	98

Abbreviations

ADR	.....	Adenoma Detection Rate
AIHW	.....	Australian Institute of Health and Welfare
ARENA	.....	Automatic Real-time ENdoscopy Assistance
ASGE	.....	American Society for Gastrointestinal Endoscopy
ASKC	.....	Adaptive scale kernel consensus technique
ANNs	.....	Artificial Neural Networks
CSIRO	.....	Commonwealth Scientific Industrial and Research Organisation
CTC	.....	Computed Tomography Colonography
CBIR	.....	Content Based Image Retrieval
DOF	.....	Degree of Freedom
EKF	.....	Extended Kalman Filter
FOBT	.....	Fecal Occult Blood Test
GLCM	.....	Grey level Co-occurrence Matrices
HA	.....	Hidden Areas behind haustral fold
HSV	.....	Hue-Saturation-Value
IVUS	.....	Intravascular Ultrasound
IPR	.....	Isolated Pixel Ratio
KLT	.....	Kanade Lucas Tomasi
MEMS	.....	Micro Electro-Mechanical System
MIS	.....	Minimal Invasive Surgery
NBI	.....	Narrow Band Imaging
OC	.....	Optical Colonoscopy
RANSAC	.....	RANdOm Sample Consensus
RF	.....	Random Forests
RGB	.....	Red-Green-Blue
RMS	.....	Root Mean Square
SIFT	.....	Scale Invariant Feature Transform
SLAM	.....	Simultaneous Localisation and Mapping
SVD	.....	Singular Value Decomposition
SURF	.....	Speed Up Robust Features
STD	.....	Standard Deviation

SFM	.....	Structure From Motion
SSD	.....	Sum of Squared Differences
TCE	.....	Tethered Capsule Endoscopy
UA	.....	Uncovered Areas which have not been observed
VO	.....	Visual Odometry
WCE	.....	Wireless Camera Endoscopy

Key Terms

Camera motion correction
Camera parameters
Classification
Colonoscope
Colorectal cancer
Computer vision
Cylindrical model
Hidden area
Machine learning
Missed polyp rate
Motion, colour and edge feature
Optical colonoscopy
Optical flow
Quality of colonoscopy
Registration
Simulator
Uncovered area
Uninformative frames
Visibility map