



THE UNIVERSITY OF  
**NEWCASTLE**  
AUSTRALIA

---

# Convolutional Neural Networks for Image Segmentation in Clinical Applications

---

INDRIANI PUSPITASARI ASTONO

BEng (Hons) (Elec.)

A thesis submitted in fulfilment of the requirements for the degree of

**Doctor of Philosophy**

**in Electrical Engineering**

August 2021

*This research was supported by an Australian Government Research Training Program*

*(RTP) Scholarship*



## **Statement of Originality**

I hereby certify that the work embodied in this thesis is my own work, conducted under normal supervision. The thesis contains no material which has been accepted, or is being examined, for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made. I give consent to the final version of my thesis being made available worldwide when deposited in the University's Digital Repository, subject to the provisions of the Copyright Act 1968.

---

**Indriani Puspitasari Astono**

BEng (Hons) (Elec.)

**August, 2021**



## Acknowledgements

---

First of all, I want to express my sincerest gratitude to my principal supervisor, A/Prof. James Welsh, for providing me with this opportunity. Thank you for all the guidance, support and patience throughout this journey. I would also like to thank my first co-supervisor, Dr. Stephan Chalup, for some invaluable advices and guidance in the early stage of my PhD. I would like to thank my second co-supervisor, Dr. Peter Greer, for the support and guidance that made the publication of the second manuscript possible. I would also like to thank Dr. Phillip Jobling and Dr. Christopher Rowe for giving me the opportunity to work with an incredibly interesting problem. Thank you for sharing your enthusiasm and knowledge with me. Thank you for your time and efforts that made the submission of the last manuscript possible.

I would also like to thank my senior, Duc Ngoc Anh Tran, for the invaluable advices and guidance in the first year of my PhD. You inspired me to complete this journey. I would also like to thank my PhD colleagues for the support and encouragement throughout this journey, especially Shashank Gupta, Fah, Siqi Pan, Jeremy Stoddard, Neda Gholizadeh and Samoda Gamage.

A special thank you to all my friends and family for the constant supports and encouragements throughout this journey. Thank you dad, brother and sister for sending me all the way to Newcastle and making sure that I was safe. Thank you Feby, Sharon, Ramizah, Annabelle, Serene and Danny for the endless long distance friendship. To all my badminton friends at Hunter Badminton, thank you for making me feel like home. I really appreciate the care and love that you all have given me. Special thanks to Prema and Geoff for the enormous support at the last bit of this

---

journey. Also, to my former English teacher, Ms. Juju, thank you for being there to answer my last minute questions.

Lastly, I want to thank Gian E. Triputra for the remarkable digital illustrations in this thesis. Thank you for making the artworks look so presentable. Most importantly, thank you for the tremendous supports and patience throughout this journey. Thank you for being there for me.

Without all of you, this would not have been possible. Thank you.

*To my mother,*

*Suarni Astono*





# Contents

---

<b>Abstract</b>	<b>v</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Background . . . . .	2
1.2 Research problem and motivation . . . . .	5
1.3 Thesis outline and contributions . . . . .	6
1.4 Publication list . . . . .	7
<b>2 Introduction to Neural Networks</b>	<b>9</b>
2.1 Introduction . . . . .	10
2.2 Neural Network Fundamentals . . . . .	10
2.2.1 Perceptron . . . . .	13
2.2.2 Multilayer Perceptron . . . . .	14
2.3 Convolutional Neural Network . . . . .	18
2.3.1 CNN Structures and Parameters . . . . .	19
2.3.2 Components of a CNN . . . . .	21
2.4 CNN Architectures . . . . .	30
2.4.1 CNN Architectures for Image Classification . . . . .	30
2.4.2 CNN Architectures for Object Detection . . . . .	33
2.4.3 CNN Architectures for Image Segmentation . . . . .	36
2.4.4 CNN Structure and Parameter Summary . . . . .	38
2.4.5 CNN Component Summary . . . . .	40
2.5 Conclusion . . . . .	41

<b>3</b>	<b>Considerations in the Implementation of a Neural Network</b>	<b>43</b>
3.1	Introduction . . . . .	44
3.2	Hyperparameters and Algorithms . . . . .	44
3.2.1	Initialisation . . . . .	44
3.2.2	Learning rate . . . . .	46
3.2.3	Momentum . . . . .	47
3.2.4	Adaptive Learning Rate . . . . .	48
3.2.5	Regularisation . . . . .	50
3.3	Data Pre-processing . . . . .	52
3.3.1	Normalisation . . . . .	52
3.3.2	Enhancement . . . . .	53
3.3.3	Augmentation . . . . .	61
3.3.4	Balancing . . . . .	62
3.4	Data Post-processing . . . . .	63
3.4.1	Mathematical Morphology . . . . .	63
3.4.2	Connected Component Labelling . . . . .	65
3.5	Evaluation Method . . . . .	67
3.6	Conclusion . . . . .	68
<b>4</b>	<b>CNN Structure and Parameter Study for a Liver Segmentation</b>	
	<b>Problem</b>	<b>69</b>
4.1	Introduction . . . . .	70
4.2	Related Work . . . . .	71
4.3	Proposed Adjacent Upsampling . . . . .	75
4.4	Proposed Network . . . . .	77
4.4.1	Proposed Network Architecture . . . . .	77
4.4.2	Configuration Detail . . . . .	81
4.5	Automatic Liver Segmentation . . . . .	81
4.5.1	Data . . . . .	82
4.5.2	Training . . . . .	83
4.5.3	Results . . . . .	84

4.6	Conclusion . . . . .	89
<b>5</b>	<b>Optimisation of a U-Net Architecture for Automatic Prostate Segmentation on MRI</b>	<b>91</b>
5.1	Introduction . . . . .	92
5.2	Dataset and Performance Metric for Optimisation . . . . .	94
5.2.1	Dataset . . . . .	94
5.2.2	Performance Metric . . . . .	95
5.3	Network Architecture Optimisation . . . . .	95
5.4	Optimised Network Architecture . . . . .	102
5.5	Prostate Segmentation using the Optimised U-Net . . . . .	104
5.5.1	Application on the Private Dataset . . . . .	104
5.5.2	Application on the PROMISE12 Dataset . . . . .	109
5.6	Discussion . . . . .	114
5.7	Conclusion . . . . .	116
<b>6</b>	<b>Objective Quantification of Nerves in Immunohistochemistry Specimens</b>	<b>117</b>
6.1	Introduction . . . . .	118
6.2	Related Work . . . . .	121
6.2.1	Colour Thresholding . . . . .	121
6.2.2	Object Detection Approaches in a WSI . . . . .	122
6.2.3	Training a Deep Learning Model . . . . .	123
6.3	Tissue Preparation and Segmentation Label Extraction . . . . .	123
6.3.1	Tissue Preparation and Digitisation . . . . .	124
6.3.2	Criteria for Nerve Detection . . . . .	124
6.3.3	Segmentation Label Extraction . . . . .	125
6.4	Nerve Detection Approach and Proposed Architecture . . . . .	126
6.4.1	Nerve Detection Approach . . . . .	127
6.4.2	Proposed Architecture . . . . .	129
6.5	Training and Results . . . . .	131
6.5.1	Dataset . . . . .	131

6.5.2	Training . . . . .	132
6.5.3	Performance Metric . . . . .	133
6.5.4	Results . . . . .	134
6.6	Discussion . . . . .	142
6.7	Additional Implementation Considerations . . . . .	143
6.7.1	Refinement of Data Representation . . . . .	143
6.7.2	Direct Implementation . . . . .	146
6.8	Conclusion . . . . .	148
<b>7</b>	<b>Conclusion and Further Research</b>	<b>149</b>
7.1	Conclusion . . . . .	150
7.2	Suggestions for Further Research . . . . .	151

# Abstract

---

The convolutional neural network (CNN) has been remarkably successful in performing automatic image segmentation in a number of clinical applications. It is able to decrease the time taken for the segmentation process as well as minimise the errors with respect to manual segmentation by a human operator. However, most of the developed CNN architectures have redundant components and trainable parameters. These redundancies cause the implementation of a CNN to be expensive in terms of time and memory usage. In this thesis, we study several CNN architectures in terms of their structures, components and number of trainable parameters to gain a deeper insight into the requirements of a CNN to achieve a state-of-the-art performance on a clinical segmentation task. As a result, we developed a CNN with a novel adjacent upsampling method that achieves a state-of-the-art performance for an organ segmentation task while being much smaller in terms of the number of trainable parameters and computation time. We developed a CNN with an optimised architecture that outperforms other state-of-the-art CNNs with similar components on an organ segmentation task. Furthermore, we developed a novel augmented classification structure to improve the performance of a segmentation network for an object detection task. We also demonstrate the implementation of a CNN on a complex digital pathology segmentation problem with the use of multiple considerations. We show that with the appropriate CNN architecture and implementation, an effective and efficient CNN based approach can be developed to assist medical experts in different segmentation problems.