# A Social Networking-Enabled Framework for Autonomous Robot Skill Development

Wei Wang

A Doctoral Dissertation Submitted for the Degree of Doctor of Philosophy

Faculty of Engineering and Information Technology

University of Technology, Sydney

October 2016

# Certificate of Authorship and Originality

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of Student

# Acknowledgements

Achieving this PhD will forever be a wonderful memory, no matter when I recall it in my life. This is not only due to living and studying in such a beautiful country and city for five and a half years, but also mostly because of the knowledge I have gained, the skills I have mastered, and the mentality I have developed from the group of kind and talented people I knew through our lab - the Magic Lab, the most vibrant lab I have seen and the place that helped me to survive this tough journey.

First, I would like to express my deepest appreciation to Professor Mary-Anne Williams, my Principal Supervisor, the person who changed my life! Thanks for her endless patience and tolerance which has allowed me to finish this PhD which was once in tough situation due to lack of funding. Thanks for her critical guidance, which has helped me go through difficult times again and again and finally enabled me to arrive to where I am now. Thanks for her innumerable innovative ideas that have enlightened me and opened my mind, allowing me to come up with solutions in my own way. Thanks for her warm smiles, which always make me forget all the unpleasantness and become sunny immediately. Thanks for her international vision, which has provided me with countless opportunities to discover and learn from so many great masters from different fields worldwide. Thanks for her insightful observations and analysis as well as her magic ability to make decisions, all of which have silently taught me what matters and what does not. As a female leader, she is an extraordinary role-model for me to emulate, to pursue a wonderful career in the future.

I would like to thank Dr Benjamin Johnston, who is my co-supervisor and also one of my close friends in the lab. He has given me countless feedbacks, comments and suggestions from the technical point of view on my topic. The innumerable joys, comfort and encouragement he has supported me with have helped me to last the distance over the PhD life span of five and a half years. He has never been angry even though we have had intense debates on particular issues every now and then. His hospitable, modest and considerate personality creates a cheerful atmosphere in the lab and that has made my PhD life even richer and happier.

In addition, I have also met several wonderful mentors, who have played indispensable roles at different stages of my PhD.

My first experience of conducting research on Robotics was in collaboration with Associate Professor Shoudong Huang in my first year when we prepared for Robocup 2011. It is his immense knowledge and unique insights on mathematics and data analysis that inspired me to build the foundation of my research on the current topic. He provided me with a good start.

Dr Wei Liu is the person who allowed me to meet with Mary-Anne. She later became an elder sister in academia as well as a close friend of mine. During my entire PhD, she has generously shared her expertise in Machine Learning and systematic way of thinking. She always finds time to help me identify problems whenever I need help, and regardless of how busy she is. For her assistance, I am particularly appreciative.

Professor Pavlos Peppas, a visiting professor in our lab, kindly initiated a meeting for me with Professor Maurice Pagnucco at UNSW, to help identify the problem when I was stuck in the last stage of this PhD. Through continuously benefitting from his insightful observations and analysis, I finally came up with skill transfer criteria in Chapter 3.

Professor Chengqi Zhang, Director of QCIS, has largely helped me in terms of developing strategical and systematic ways of thinking, and in developing crucial skills in organisation and leadership. He has also provided a range of financial opportunities to help cover my living expenses. His consistent encouragement, comfort and inspiration have provided indispensable support in my struggle throughout the whole journey. I was very fortunate to meet him during my PhD!

Professor Sean He and his student Minqi Li generously shared their knowledge in the field of Vision, which helped me to identify my hypotheses in that discipline.

I also have benefited a great deal from the discussions with Professor Robert Davison from City University of Hong Kong. In spite of working in separate fields, the "Social Theory" he shared provided me with a deeper understanding of the potential and feasibility of building a social network for robots. In addition, his set of questions helped me to systematically identify specific issues when my research was not going smoothly. His guidance significantly helped me to quickly get back on track.

I would like to especially thank Professor Xiaoping Chen, A/Professor Jianmin Ji, and A/Professor Feng Wu, as well as research students in the Multi-Agent Autonomous Robot Lab at the University of Science and Technology of China (USTC), for their valuable comments on how to polish and extend the thesis draft during my visit. In particular, they generously introduced me to joint work on an international research collaboration, which is valuable to a PhD student who is about to graduate.

Chunguang Qu, one of my best personal friends in China, has excelled in Physics, Mathematics, Biology as well as Computer Science. He has spared no effort to share with me countless valuable suggestions and ideas from a trans-disciplinary point of view during my PhD in order to broaden the scope of my knowledge and my way of thinking about the current research and dissertation. He also provided me with significant help in developing the simulation in Chapter 7.

This dissertation could not have been achieved without valuable discussions with PhD colleagues, capstone students and visiting students in the Magic Lab. My PhD colleagues: Jebrin Sharawneh, Xun Wang, Shan Chen, Chris Stanton, Rony Novianto, Sylvan Rudduck, Pramod Parajuli, Muh Anshar, Shaukat Abedi, Nima Ramezani Taghiabadi, Robert Lange, Jonathan Vitale, Mahya Mirzaei Poueinag, Syed Ali Raza and Daniel Cowen. Capstone students: Edward Ratanasena, Leigh Dearden, Ryan Parry-Jones, Michelle Youssef and Jenny Lui. Visiting students: Henry Xue and Fangkai Yang from USTC, China, Saleha Raza from IBA, Pakistan and Henry Bard from USC, USA.

This dissertation also could not have been achieved without the company of the Chinese students and friends I met at UTS. My Chinese classmates at UTS: Jing Jiang, Can Wang, Shirui Pan, Chang Liu, Lei Shi, Xuyun Zhang, Chao Zeng, Nuo Du, Weiming Liu, Minqi Li, Sheng Wang, Liangfu Lu, Yi Ji, Yifan Fu, Dianshuang Wu, Hongshu Chen, Zhibin Hong, Guodong Long, Wei Bian, Tianyi Zhou, Maoying Qiao, MingSong Mao, and Tongliang Liu, to name a few. They shared their expertise in their fields, which inspired me to think about my topic from different angles. They gave me advice when I was confused about specific problems and always passionately assisted me with any experiments conducted in the lab when needed.

I also owe a big "Thank You" to UTS Graduate Research School and Faculty of Engineering and Information Technology (FEIT) of UTS, especially Professor Jie Lu, Phyllis Agius and Craig Shuard from FEIT, for their timely and kindly help in dealing with time-consuming administrative matters. Without their endeavours, this PhD dissertation could not have been realised.

I also need to say a big "Thank You" to IBM, which generously offered me a prestigious IBM Fellowship, which highlights the value of my topic and has given me tremendous courage and confidence in developing this dissertation.

Finally, the endless love from my parents is the fertile ground from which I have derived the strength, courage, confidence and mental strength to independently pursue my dream in a foreign country. My parents are the best I have ever seen. They have spared no effort in supporting my decision from the beginning to the end but have always hidden their strong longing for their only daughter in front of me at all times. For their patience, massive love and tremendous efforts on my behalf, I hope this dissertation will be the best reward!

# Table of Contents

# List of Figures

# List of Tables

# Abstract

Intelligent service robots will need to adapt to unforeseen situations when performing tasks for humans. To do this, they will be expected to continuously develop new skills. Existing frameworks that address robot learning of new skills for a particular task often follow a task-specific design approach. Task-specific design is unable to support robots to adapt new skills to new tasks. This is largely due to the inability of skill specification in task-specific design to be extended or to be easily changed.

This dissertation provides an innovative task-independent framework that allows robots to develop new skills on their own. The idea is to create an online social network platform called Numbots that enables robots to learn new skills autonomously from their social circles. This platform integrates a state-of-the-art approach to learning from experience, called Constructing Skill Trees (CST), with a state-of-the-art framework for knowledge sharing, called RoboEarth. Based on this integration, a new logic model for online Robot-Robot Interaction (RRI) is developed.

The principal focus of this dissertation is the analysis of, and solutions to three underlying technical challenges required to achieve the RRI model: (i) skill representation; (ii) autonomous skill recognition and sharing; and (iii) skill transfer.

We focus on motion skills required to interact with and manipulate objects where a robot performs a series of motions to attain a goal given by humans. Skills formalise robot activities, which may involve an object (for example, kicking a ball, lifting a box, or passing a bottle of water to a person). Skills may also include robot activities that do not involve objects (for example, raising hands or walking forward).

The first challenge concerns how to create a new skill representation that can represent robot skills independently of robot species, tasks and environments. We develop a *generic robot skill representation*, which characterises three key dimensions of a robot skill in the focused domain: the *changing*

*relationship*, the *spatial relationship* and the *temporal relationship* between the robot and a possible object. The new representation takes a spatial-temporal perspective similar to that found in RoboEarth, and uses the concepts of "agent space" and "object space" from the CST approach.

The second challenge concerns how to enable robots to autonomously recognise and share their experiences with other robots that are in their social network. We propose an *effect-based skill recognition* mechanism that enables robots to recognise skills based on the effects that result from their action. We introduce two types of autonomous skill recognition: (i) recognition of a chain of existing skill primitives; (ii) recognition of a chain of unknown skills. All recognised skills are generalised and packed into a JSON file to share across Numbots.

The third challenge is how to enable shared generic robot skills to be interpreted by a robot learner for its own problem solving. We introduce an *effect-based skill transfer mechanism*, an algorithm to decompose and customise the downloaded generic robot skill into a set of executable action commands for the robot learner's own problem solving.

After the introduction of three technical challenges of the RRI model and our solutions, a simulation is undertaken. It demonstrates that a skill recognised and shared by a PR2 robot can be reused and transferred by a NAO robot for a different problem solving. In addition, we also provide a series of comparisons with RoboEarth with a use case study "ServeADrink" to demonstrate the key advantages of the newly created generic robot skill representation over the limited skill representation in RoboEarth.

Even though implementation of Numbots and the RRI model on a real robot remains as future work, the proposed analysis and solutions in this dissertation have demonstrated the potential to enable robots to develop new skills on their own, in the absence of human/robot demonstrators and to perform a task for which the robot was not explicitly programmed.