





# Flexible Attention-based Cognitive Architecture for Robots

---

**Rony Novianto**

Submitted to the  
Faculty of Engineering and Information Technology  
University of Technology, Sydney  
in partial fulfillment of the requirements for the degree of  
Doctor of Philosophy (Computer Science)  
2014



**CERTIFICATE OF AUTHORSHIP/ORIGINALITY**

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as a 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.

Rony Novianto

# Acknowledgement

This research would not have been possible without the support of following people and organisations who I would also like to thank:

- **Professor Mary-Anne Williams** (University of Technology Sydney, Australia): my research supervisor, who provided me with countless support, opportunities, feedback, suggestions and advice throughout my candidature.
- **Doctor Benjamin Johnston** (University of Technology Sydney, Australia): who kindly spent the time to provide me with enormous feedback and suggestions, as well as to review this dissertation.
- **My fellow students** in the Innovation and Enterprise Research Laboratory: who made the laboratory a friendly and productive environment for working on my research.
- **Professor Xiaoping Chen (陈小平教授)** (University of Science and Technology of China (USTC), China): who generously hosted me for collaborating with his research laboratory.
- **Professor Peter Gärdenfors** (Lund University, Sweden): who generously hosted me for my Australian Endeavour Award.
- **Professor Christian Balkenius** (Lund University, Sweden): who generously hosted me for my Australian Endeavour Award.
- **The students** in Professor Xiaoping Chen's Multi-Agent Systems Laboratory, Professor Peter Gärdenfors' laboratory and Professor Christian Balkenius' laboratory: who warmly welcomed me into their research group.
- **Glenn Wightwick** (previously at International Business Machines (IBM), Australia, and currently at University of Technology Sydney, Australia): who

continuously supported my work.

- **Professor Michael Genesereth** (Stanford University, USA): my examiner for this dissertation who provided me with invaluable and kind feedback, suggestions and advice.
- **Doctor Paul Robertson** (Massachusetts Institute of Technology, USA): my examiner for this dissertation who provided me with invaluable and kind feedback, suggestions and advice.
- **Professor Reid Simmons** (Carnegie Mellon University, USA): my examiner for this dissertation who provided me with invaluable and kind feedback, suggestions and advice.
- **Australian Government and IBM**: who supported me under Australian Research Council (ARC) Discovery Project Grant and provided me with Australian Endeavour Fellowship Award 2011 and IBM Ph.D. Fellowship Award 2011.
- **My parents, family, partner and friends**: who continuously and patiently supported me throughout my difficulties.
- **My sister and first nephew**: who patiently waited and endured pain when I was busy working.

# Abstract

Robots have been working in factories to achieve tasks autonomously with little human intervention for some time. Even though robots are commonly found as vacuum cleaners in homes and assistants in hospitals, by comparison with factory robots, service robots have not been widely deployed in society because there remains several challenges deploying robots to achieve complex tasks in open, unstructured, uncontrolled and complex environments.

Critical research gaps arise from the lack of cognitive architectures that support robots to undertake tasks in open and complex environments. Throughout the history of AI, researchers have developed various algorithms, representations and mechanisms, to solve specific tasks. However, each of these techniques has different strengths and weaknesses when applied to particular problems. A cognitive architecture provides a unifying infrastructure that can integrate various techniques to solve open and complex tasks.

However, four important issues become apparent when current cognitive architectures are applied to service robotic tasks. First, they are not capable of managing robot resources and as a result robotic developers must take responsibility for managing the resources manually. Second, they are not capable of integrating independently developed techniques, which are often needed to solve problems. Third, they are inflexible, unable to adapt to design changes and require considerable time and effort to modify. Fourth, they are inadequate for supporting the necessary capabilities required by robots such as multiple goals, reliability and maintainability. These issues are confirmed when cognitive architectures are applied to a standard benchmark problem in AI: the autonomous robot soccer problem.

The purpose of this dissertation is to address these significant gaps so as to accelerate the development, deployment and adoption of service robots undertaking tasks in open and complex environments. This dissertation develops a novel bio-



inspired cognitive architecture (called ASMO) that has been designed and developed to address all four identified shortcomings of current cognitive architectures.

In ASMO, intelligent behaviours to solve open and complex tasks is a result of the emergence of constituent processes, rather than from careful top-down control engineering. Minsky has argued in his *Society of Mind* that intelligent behaviours can emerge from the interaction of many simple processes, even though each process may lack ‘intelligence’ in isolation. In addition, Anderson argued that an emergent system produces more complex behaviours and properties that cannot be reduced to the sum of its components.

ASMO has attention, emotion and learning mechanisms that are inspired by human intelligence. It treats each action as a concurrent, independent and self-governed black box process that competes for the robot’s attention to perform actions. The attention mechanism is used to mediate the competition among processes, which correspond to the set of potential actions. The emotion mechanism is used to bias the attention demanded by the processes. The learning mechanisms are used to modify the attention in order to improve robots’ performances.

Combining concurrent, independent and self-governed black-box processes with attention and emergent approaches allows ASMO to address the four shortcomings of current cognitive architectures. First, the attention mechanism manages resources explicitly. Second, the black-box design allows any kind of independently developed technique to be integrated without the need to know its internal algorithm, representation or mechanism. Third, attention weighted values enables various techniques to be (re)integrated or (re)structured on the fly with considerably less time and effort. Fourth, the concurrent, independent and self-governed designs support the capabilities required by robots by allowing processes to (i) achieve multiple goals concurrently, (ii) fail without causing the whole system to fail and (iii) be maintained in isolation.

ASMO is evaluated using two robotic problems: (i) the RoboCup soccer standard benchmark problem is used to demonstrate proof-of-concept that a team of robots can be supported by ASMO. In particular, a real robot can be governed by ASMO’s attention mechanism to undertake complex tasks. (ii) a companion robot problem is used to demonstrate that ASMO’s attention, emotion and learning mechanisms overcome the four identified shortcomings of current state-of-the-art cognitive architectures.

This dissertation presents ASMO, an innovative cognitive architecture that addresses the four shortcomings of current state-of-the-art cognitive architectures, and that can also accelerate the development, deployment and adoption of service robots. ASMO provides a more natural and easier approach to programming robots based on a novel bio-inspired attention management system. ASMO allows researchers and robot system developers to focus on developing new capabilities as processes rather than having to be concerned about integrating new capabilities into a cognitive architecture.

# Contents

|          |   |           |
|----------|---|-----------|
| <b>1</b> | <b>Introduction</b>                                       | <b>1</b>  |
| 1.1      | Scientific Challenge and Motivation . . . . .             | 3         |
| 1.2      | Aims and Objectives . . . . .                             | 6         |
| 1.3      | Significance and Contributions . . . . .                  | 6         |
| 1.4      | Scope . . . . .   | 8         |
| 1.5      | Dissertation Organisation . . . . .                       | 9         |
| <br>     |   |           |
| <b>2</b> | <b>Robot Cognitive Architecture</b>                       | <b>11</b> |
| 2.1      | Definition of Robot . . . . .                             | 11        |
| 2.2      | Robot Environment . . . . .                               | 14        |
| 2.3      | Definition of Intelligence . . . . .                      | 16        |
| 2.4      | Definitions of Cognitive Architecture . . . . .           | 19        |
| 2.4.1    | Comparison with Other Types of Software . . . . .         | 21        |
| 2.5      | Evaluation Criteria for Cognitive Architectures . . . . . | 24        |
| <br>     |   |           |
| <b>3</b> | <b>Existing Cognitive Architectures</b>                   | <b>27</b> |
| 3.1      | Approaches based on Knowledge Design . . . . .            | 27        |
| 3.2      | Approaches based on Knowledge Utilisation . . . . .       | 29        |
| 3.2.1    | Lookup-based Approach . . . . .                           | 31        |
| 3.2.2    | Case-Based Finite State Machine Approach . . . . .        | 32        |

|          |   |           |
|----------|---|-----------|
| 3.2.3    | Priority-based or Hierarchical-based Approach . . . . .     | 34        |
| 3.2.4    | Goal-based Approach . . . . .                               | 35        |
| 3.2.5    | Connection-based Approach . . . . .                         | 37        |
| 3.2.6    | Utility-based Approach . . . . .                            | 39        |
| 3.3      | Current State of The Art . . . . .                          | 40        |
| 3.3.1    | Soar . . . . .  | 42        |
| 3.3.2    | Adaptive Control of Thought – Rational (ACT-R) . . . . .    | 45        |
| 3.3.3    | Subsumption . . . . .                                       | 49        |
| 3.3.4    | Situated Automata . . . . .                                 | 51        |
| 3.3.5    | Procedural Reasoning System (PRS) . . . . .                 | 53        |
| 3.3.6    | Agent Network Architecture (ANA) . . . . .                  | 55        |
| 3.3.7    | ICARUS . . . . .  | 59        |
| 3.3.8    | Three Tier / Three Layers Architecture (3T) . . . . .       | 62        |
| 3.3.9    | Polyscheme . . . . .  | 64        |
| 3.4      | Related Architectures . . . . .                             | 67        |
| 3.5      | Summary and Gaps . . . . .                                  | 70        |
| <b>4</b> | <b>ASMO Cognitive Architecture</b>                          | <b>73</b> |
| 4.1      | Overall Design . . . . .                                    | 73        |
| 4.1.1    | Memory . . . . .  | 75        |
| 4.1.2    | Attention Mechanism . . . . .                               | 77        |
| 4.1.3    | Emotion Mechanism . . . . .                                 | 78        |
| 4.1.4    | Learning Mechanisms . . . . .                               | 78        |
| 4.2      | Share Management of Resources . . . . .                     | 80        |
| 4.3      | Cognitive Capabilities . . . . .                            | 81        |
| 4.3.1    | Outer World, Inner World, Sensation and Actuation . . . . . | 82        |

---

|          |   |            |
|----------|---|------------|
| 4.3.2    | Perception, Conception, Simulation and Planning . . . . . | 83         |
| <b>5</b> | <b>ASMO's Attention Mechanism</b>                         | <b>85</b>  |
| 5.1      | Need for Attention in Decision Making . . . . .           | 85         |
| 5.2      | Theories of Attention . . . . .                           | 87         |
| 5.2.1    | Selective or Focused Attention . . . . .                  | 87         |
| 5.2.2    | Divided Attention . . . . .                               | 89         |
| 5.2.3    | Automaticity . . . . .                                    | 91         |
| 5.3      | Computational Design and Model . . . . .                  | 93         |
| 5.4      | Implementation . . . . .                                  | 97         |
| 5.4.1    | Modules . . . . .   | 99         |
| 5.4.2    | Attention Value . . . . .                                 | 103        |
| 5.4.3    | Boost Value and Reflex Priority . . . . .                 | 106        |
| 5.4.4    | Attention Competition . . . . .                           | 107        |
| 5.5      | Other Work . . . . .                                      | 112        |
| <b>6</b> | <b>ASMO's Emotion Mechanism</b>                           | <b>119</b> |
| 6.1      | Needs for Emotion and Subjective Bias . . . . .           | 119        |
| 6.2      | Theories of Emotion . . . . .                             | 121        |
| 6.2.1    | Representation . . . . .                                  | 121        |
| 6.2.2    | Causality . . . . .                                       | 123        |
| 6.2.3    | Evaluation: Innate or Learned . . . . .                   | 126        |
| 6.3      | Computational Design and Model . . . . .                  | 127        |
| 6.4      | Implementation . . . . .                                  | 131        |
| 6.4.1    | Dimension and Label Nodes . . . . .                       | 132        |
| 6.4.2    | Biological Factor and Cognitive Factor Nodes . . . . .    | 133        |
| 6.4.3    | Subjective Weight . . . . .                               | 134        |

---

|          |   |            |
|----------|---|------------|
| 6.5      | Other Work . . . . .                                    | 138        |
| <b>7</b> | <b>ASMO's Learning Mechanisms</b>                       | <b>140</b> |
| 7.1      | Needs for Learning . . . . .                            | 140        |
| 7.2      | Theories of Learning . . . . .                          | 141        |
| 7.2.1    | Habituation and Sensitisation . . . . .                 | 141        |
| 7.2.2    | Operant Conditioning . . . . .                          | 143        |
| 7.2.3    | Classical Conditioning . . . . .                        | 144        |
| 7.2.4    | Observational Learning . . . . .                        | 145        |
| 7.3      | Computational Design and Model . . . . .                | 146        |
| 7.4      | Implementation . . . . .                                | 147        |
| 7.4.1    | Habituation and Sensitisation . . . . .                 | 148        |
| 7.4.2    | Operant Conditioning . . . . .                          | 150        |
| 7.4.3    | Classical Conditioning . . . . .                        | 152        |
| 7.4.4    | Observational Learning . . . . .                        | 153        |
| 7.5      | Other Work . . . . .                                    | 156        |
| 7.5.1    | Habituation and Sensitisation . . . . .                 | 156        |
| 7.5.2    | Operant Conditioning . . . . .                          | 159        |
| 7.5.3    | Classical Conditioning . . . . .                        | 160        |
| 7.5.4    | Observational Learning . . . . .                        | 162        |
| <b>8</b> | <b>Evaluation</b>                                       | <b>165</b> |
| 8.1      | RoboCup Soccer SPL Standard Benchmark Problem . . . . . | 165        |
| 8.1.1    | ASMO's Attention Mechanism . . . . .                    | 170        |
| 8.1.2    | ASMO's Emotion and Learning Mechanisms . . . . .        | 175        |
| 8.2      | Smokey Robot Companion Problem . . . . .                | 177        |
| 8.2.1    | ASMO's Attention Mechanism . . . . .                    | 181        |

---

|          |   |            |
|----------|---|------------|
| 8.2.2    | ASMO's Emotion Mechanism . . . . .                              | 186        |
| 8.2.3    | ASMO's Habituation and Sensitisation Mechanisms . . . . .       | 189        |
| 8.2.4    | ASMO's Operant Conditioning Mechanism . . . . .                 | 194        |
| 8.2.5    | ASMO's Classical Conditioning Mechanism . . . . .               | 196        |
| 8.2.6    | ASMO's Observational Learning Mechanism . . . . .               | 200        |
| 8.3      | Analysis and Discussion . . . . .                               | 201        |
| <b>9</b> | <b>Conclusion</b>   | <b>208</b> |
| 9.1      | Significance and Contributions . . . . .                        | 208        |
| 9.2      | Limitation and Future Work . . . . .                            | 210        |
| 9.3      | Final Thoughts . . . . .  | 212        |
| <b>A</b> | <b>Non-Cognitive Architectures</b>                              | <b>214</b> |
| A.1      | Autonomous Robot Architecture (AuRA) . . . . .                  | 214        |
| A.2      | Distributed Architecture for Mobile Navigation (DAMN) . . . . . | 216        |
| A.3      | Emotionally Grounded (EGO) Architecture . . . . .               | 219        |

# List of Figures

|      |   |    |
|------|---|----|
| 1.1  | Assistance Needed for People with Disability by Tasks . . . . . | 2  |
| 1.2  | The Current Standardised Hardware Platform for 2014 . . . . .   | 4  |
| 2.1  | Classification of Agents . . . . .                              | 12 |
| 2.2  | Cognitive Architecture and Other Software . . . . .             | 22 |
| 3.1  | Decision Making Categories . . . . .                            | 29 |
| 3.2  | Competitive vs. Collective Decision Making . . . . .            | 30 |
| 3.3  | Priority Scenario . . . . .                                     | 35 |
| 3.4  | Neural Network Example . . . . .                                | 38 |
| 3.5  | Robots Governed by Soar . . . . .                               | 42 |
| 3.6  | Soar Architecture [120] . . . . .                               | 44 |
| 3.7  | Robots Governed by ACT-R . . . . .                              | 46 |
| 3.8  | ACT-R Architecture . . . . .                                    | 47 |
| 3.9  | Subsumption Layer [42] . . . . .                                | 49 |
| 3.10 | Subsumption Module [42] . . . . .                               | 50 |
| 3.11 | Circuit Generated by Gapps . . . . .                            | 52 |
| 3.12 | Procedural Reasoning System . . . . .                           | 54 |
| 3.13 | Agent Network Architecture . . . . .                            | 56 |
| 3.14 | Robots Governed by ICARUS . . . . .                             | 59 |



---

|      |  |     |
|------|--|-----|
| 3.15 | ICARUS Architecture . . . . .  | 61  |
| 3.16 | Three Tier / Three Layers Architecture [34] . . . . .                            | 62  |
| 3.17 | Robots Governed by Polyscheme . . . . .  | 65  |
| 4.1  | Robots Governed by ASMO . . . . .  | 74  |
| 4.2  | ASMO Cognitive Architecture . . . . .  | 74  |
| 4.3  | Cognitive Capabilities proposed by Gärdenfors and Williams . . . . .             | 82  |
| 4.4  | ASMO Body . . . . .  | 83  |
| 5.1  | Attention Competition or Election . . . . .                                      | 98  |
| 6.1  | Theories of Emotional Causality . . . . .  | 124 |
| 6.2  | Design of ASMO's Emotion Mechanism . . . . .                                     | 128 |
| 6.3  | Types of Nodes Used by ASMO's Emotion Mechanism . . . . .                        | 132 |
| 7.1  | Neural Networks for Observational Learning . . . . .                             | 154 |
| 8.1  | RoboCup Soccer Scenario . . . . .  | 167 |
| 8.2  | Pseudocode of Some Modules Used in RoboCup Soccer System . . . . .               | 171 |
| 8.3  | Attentional Decision Making in The RoboCup Soccer SPL Competition 2010 . . . . . | 176 |
| 8.5  | Neural Network Used by The attend_motion Module . . . . .                        | 182 |
| 8.6  | Attentional Decision Making in Smokey . . . . .                                  | 186 |
| 8.7  | Causal Bayesian Network Used in Smokey . . . . .                                 | 187 |
| 8.8  | Experiments of Emotional Subjective Bias in Smokey . . . . .                     | 190 |
| 8.9  | Habituation and Sensitisation Learning Experiment in Smokey . . . . .            | 192 |
| 8.9  | Experiments of Habituation and Sensitisation Learning in Smokey . . . . .        | 193 |
| 8.10 | Experiments of Operant Conditioning Learning in Smokey . . . . .                 | 197 |
| 8.11 | Experiments of Classical Conditioning Learning in Smokey . . . . .               | 199 |

|   |     |
|---|-----|
| 8.12 The Neural Network of The Observational Learning in Smokey Robot Companion . . . . . | 200 |
| 8.13 Experiments of Observational Learning in Smokey . . . . .                            | 202 |
| A.1 Robots Governed by AuRA . . . . .   | 215 |
| A.2 DAMN Constraint Arbitration [186] . . . . .   | 217 |
| A.3 DAMN Actuation Arbitration [186] . . . . .  | 217 |
| A.4 DAMN Effect Arbitration [186] . . . . .   | 218 |
| A.5 Robots Governed by EGO . . . . .  | 220 |
| A.6 EGO Architecture . . . . .  | 222 |
| A.7 An Example of A Module Tree Structure in EGO Architecture . . . . .                   | 222 |

# List of Tables

|     |   |     |
|-----|---|-----|
| 3.1 | Lookup Table Example . . . . .  | 32  |
| 3.2 | Priority Table Example . . . . .  | 34  |
| 3.3 | Action Description Table Example . . . . .  | 36  |
| 3.4 | Comparison to Bryson's Trend of Cognitive Architectures . . . . .                           | 41  |
| 3.5 | Comparison of Approaches in Cognitive Architecture based on Knowledge Design . . . . .      | 70  |
| 3.6 | Comparison of Approaches in Cognitive Architecture based on Knowledge Utilisation . . . . . | 71  |
| 3.7 | Comparison of Current State of The Art of Cognitive Architectures . . . . .                 | 72  |
| 5.1 | Stroop Effect . . . . .   | 91  |
| 5.2 | Effects for Different Rates in Attention Value . . . . .                                    | 106 |
| 8.1 | Users' Preferences of Playing Ball and Drums . . . . .                                      | 183 |
| 8.2 | The Subjective Weights of the play_ball and play_drums Modules . . . . .                    | 188 |
| 8.3 | Users' Requests . . . . .   | 198 |
| 8.4 | Probability of Requests Asked by Users . . . . .  | 198 |

