

# Table of Contents

|                                                             |      |
|-------------------------------------------------------------|------|
| <b>Preface</b> .....                                        | v    |
| <b>Summary</b> .....                                        | vii  |
| <b>Acronyms</b> .....                                       | xvii |
| <b>1. Introduction</b> .....                                | 1    |
| 1.1 Topic .....                                             | 1    |
| 1.2 Hardware Evolution .....                                | 2    |
| 1.2.1 An Example of Reconfigurable Hardware .....           | 2    |
| 1.2.2 Evolving the Circuit Configuration .....              | 4    |
| 1.2.3 Intrinsic/Extrinsic .....                             | 6    |
| 1.3 Motivation .....                                        | 7    |
| 1.4 The Thesis .....                                        | 7    |
| <b>2. Context</b> .....                                     | 9    |
| 2.1 Inspiration .....                                       | 9    |
| 2.1.1 Mead et al.: Analog neural VLSI .....                 | 9    |
| 2.1.2 Pulse-stream Neural Networks .....                    | 11   |
| 2.1.3 Other Neural Hardware .....                           | 11   |
| 2.1.4 Reconfigurable Hardware .....                         | 12   |
| 2.1.5 Self-Timed Digital Design .....                       | 15   |
| 2.1.6 Analogies with Software: Ray's Tierra.....            | 16   |
| 2.1.7 A Dynamical Systems Perspective .....                 | 16   |
| 2.2 Evolutionary Algorithms for Electronic Design:          |      |
| Other approaches.....                                       | 17   |
| 2.2.1 ETL .....                                             | 17   |
| 2.2.2 de Garis.....                                         | 20   |
| 2.2.3 EPFL & CSEM: 'Embryonics' .....                       | 23   |
| 2.2.4 A Sophisticated Extrinsic Approach: Hemmi et al. .... | 24   |
| 2.2.5 Evolving Analogue Circuits .....                      | 25   |
| 2.2.6 A Silicon Neuromorph – The First Intrinsic Hardware   |      |
| Evolution? .....                                            | 26   |
| 2.2.7 Loosely Related Evolutionary Hardware Projects .....  | 27   |

|                                                                                                 |                                                                                                         |           |
|-------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|-----------|
| 2.3                                                                                             | Multi-Criteria EAs: Area, Power, Speed and Testability . . . . .                                        | 27        |
| 2.4                                                                                             | A Philosophy of Artificial Evolution . . . . .                                                          | 29        |
| 2.4.1                                                                                           | Domain Knowledge, Morphogenesis, Encoding Schemes<br>and Evolvability . . . . .                         | 29        |
| 2.4.2                                                                                           | Species Adaptation Genetic Algorithms (SAGA) . . . . .                                                  | 32        |
| 2.5                                                                                             | The Position of this Book Within the Field . . . . .                                                    | 33        |
| <b>3.</b>                                                                                       | <b>Unconstrained Structure and Dynamics . . . . .</b>                                                   | <b>35</b> |
| 3.1                                                                                             | The Relationship Between Intrinsic Hardware Evolution<br>and Conventional Design Techniques . . . . .   | 35        |
| 3.2                                                                                             | Unconstrained Structure . . . . .                                                                       | 37        |
| 3.3                                                                                             | Unconstrained Dynamics . . . . .                                                                        | 38        |
| 3.3.1                                                                                           | Unconstrained Evolutionary Manipulation of Timescales<br>I: Simulation study . . . . .                  | 40        |
| 3.3.2                                                                                           | II: Using a real FPGA . . . . .                                                                         | 44        |
| 3.3.3                                                                                           | A Showpiece for Unconstrained Dynamics:<br>An Evolved Hardware Sensorimotor Control Structure . . . . . | 48        |
| 3.4                                                                                             | The Relationship Between Intrinsic Hardware<br>Evolution and Natural Evolution . . . . .                | 56        |
| <b>4.</b>                                                                                       | <b>Parsimony and Fault Tolerance . . . . .</b>                                                          | <b>57</b> |
| 4.1                                                                                             | Insensitivity to Genetic Mutations . . . . .                                                            | 57        |
| 4.2                                                                                             | Engineering Consequences of Mutation-Insensitivity . . . . .                                            | 62        |
| 4.3                                                                                             | Explicitly Specifying Fault-Tolerance Requirements . . . . .                                            | 66        |
| 4.4                                                                                             | Adaptation to Faults . . . . .                                                                          | 70        |
| 4.5                                                                                             | Fault Tolerance Through Redundancy . . . . .                                                            | 71        |
| 4.6                                                                                             | Summary . . . . .                                                                                       | 71        |
| <b>5.</b>                                                                                       | <b>Demonstration . . . . .</b>                                                                          | <b>73</b> |
| 5.1                                                                                             | The Experiment . . . . .                                                                                | 73        |
| 5.2                                                                                             | Results . . . . .                                                                                       | 76        |
| 5.3                                                                                             | Analysis . . . . .                                                                                      | 80        |
| 5.4                                                                                             | Interpretation . . . . .                                                                                | 84        |
| <b>6.</b>                                                                                       | <b>Future Work . . . . .</b>                                                                            | <b>87</b> |
| 6.1                                                                                             | Engineering Tolerances . . . . .                                                                        | 87        |
| 6.2                                                                                             | Applications . . . . .                                                                                  | 91        |
| <b>7.</b>                                                                                       | <b>Conclusion . . . . .</b>                                                                             | <b>93</b> |
| <b>Appendix A. Circuit Diagram of the DSM Evolvable<br/>Hardware Robot Controller . . . . .</b> |                                                                                                         | <b>97</b> |

**Appendix B. Details of the Simulations used in the**  
                  **‘Mr Chips’ Robot Experiment . . . . . 99**  
    B.1 The Motor Model . . . . . 99  
    B.2 The Movement Model . . . . . 100  
    B.3 The Sonar Model . . . . . 100  
**References . . . . . 103**