

DE GRUYTER
OLDENBOURG

Lukas König

COMPLEX BEHAVIOR IN EVOLUTIONARY ROBOTICS



Lukas König

Complex Behavior in Evolutionary Robotics

DE GRUYTER
OLDENBOURG

Mathematics Subject Classification 2010

68-02, 68M14, 68N19, 68N30, 68Q32, 68Q45, 68T05, 68T40, 68U20, 90C40, 93C85

Author

Dr. Lukas König
Karlsruhe Institute of Technology (KIT)
Institute of Applied Informatics and Formal
Description Methods (AIFB)
KIT-Campus Süd
76128 Karlsruhe, Germany
lukas.koenig@kit.edu

“Towards Complex Behavior in Evolutionary Robotics”

Von der Fakultät für Wirtschaftswissenschaften des Karlsruher Instituts für Technologie
genehmigte Dissertation

Datum der Prüfung: 25. Juni 2014

Referent: Prof. Dr. Hartmut Schmeck

Korreferent: Prof. Dr. Marius Zöllner

The author thanks Benjamin Bolland, Maximilian Heindl, Junyoung Jung, Serge Kernbach, Daniel Pathmaperuma and Holger Prothmann for kindly supplying photographs, and the Graphviz open source team for the free visualization software Graphviz.

ISBN 978-3-11-040854-6

e-ISBN (PDF) 978-3-11-040855-3

e-ISBN (ePUB) 978-3-11-040918-5

Set-ISBN 978-3-11-040917-8

Library of Congress Cataloging-in-Publication Data

A CIP catalog record for this book has been applied for at the Library of Congress.

Bibliographic information published by the Deutsche Nationalbibliothek

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at <http://dnb.dnb.de>.

© 2015 Walter de Gruyter GmbH, Berlin/Munich/Boston

Cover illustration: Benjamin Bolland

Printing and binding: CPI books GmbH, Leck

♻️ Printed on acid-free paper

Printed in Germany

www.degruyter.com



Lukas König

Complex Behavior in Evolutionary Robotics

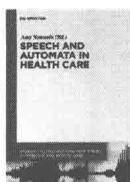
Also of interest



Robots that Talk and Listen

Judith Markowitz (Ed.), 2014

ISBN 978-1-61451-603-3, e-ISBN (PDF) 978-1-61451-440-4,
e-ISBN (EPUB) 978-1-61451-915-7, Set-ISBN 978-1-61451-441-1



Speech and Automata in Health Care

Amy Neustein, 2014

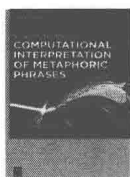
ISBN 978-1-61451-709-2, e-ISBN (PDF) 978-1-61451-515-9,
e-ISBN (EPUB) 978-1-61451-960-7, Set-ISBN 978-1-61451-516-6



Technische Assistenzsysteme

Wolfgang Gerke, 2014

ISBN 978-3-11-034370-0, e-ISBN (PDF) 978-3-11-034371-7,
e-ISBN (EPUB) 978-3-11-039657-7



Computational Interpretation of Metaphoric Phrases

Sylvia Weber Russel, 2015

ISBN 978-1-5015-1065-6, e-ISBN (PDF) 978-1-5015-0217-0,
e-ISBN (EPUB) 978-1-5015-0219-4, Set-ISBN 978-1-5015-0218-7

Acknowledgements

This book presents and concludes a major part of my research conducted from early 2007 until today. By far the greatest fraction of this time and, more importantly, the best of the presented ideas are strongly connected to the Institute AIFB where I worked as a research associate since December 2007. Here, my advisor Prof. Hartmut Schmeck gave me the opportunity to follow my research interests virtually limit-free in a creative and inspirational working environment, for which I am deeply grateful to him. I also thank him for his support and trust, even in difficult times, and for his constructive, detailed, often seemingly pedantic remarks which repeatedly led me to a better understanding of my own work.

However, as I will show in the book, any environment is inextricably linked with the agents acting in it, and this is particularly true of a working environment. Therefore, I am just as grateful to all my colleagues (former and current) for being so creative and inspirational, and for simply constituting an enjoyable company. In particular, I thank (in order of appearance) Sanaz Mostaghim, Ingo Paenke, Felix Vogel, Holger Prothmann, André Wiesner, Daniel Pathmaperuma, Christian Hirsch, Marc Mültin, Friederike Pfeiffer-Bohnen, Pradyumn Shukla, Micaela Wünsche, Fabian Rigoll, Fredy Rios and Marlon Braun for some of the most valuable (in very different ways) scientific discussions I ever had. Furthermore, I thank Ingo Mauser, Daniel Pathmaperuma, Friederike Pfeiffer-Bohnen and Felix Vogel for proofreading early, probably rather unpleasant versions of the manuscript.

Creating a doctoral thesis, including the many tasks it brings along, required the so far greatest effort of my life. This amount of work cannot be handled without being backed up in the “real world”.

I thank my old friends, who never stopped being there for me, sometimes in person, always in my mind, and my new friends, the best of whom emerged from being mere colleagues at first, for reminding me of life beyond work. I am greatly thankful to my parents for encouraging me in not being satisfied with common opinions (which may well have become my most noticeable character trait today), to my grandfather for revealing me the joy of exploring everything and telling it to everybody (i. e., research and teaching) and to my grandmother for reminding me of the importance of studying (i. e., life beyond amusement). I adore my wife for showing me – a computer scientist – the beauty of nature (which may have given the thesis an esoteric touch at one place or another). Finally, I am most notably grateful to my whole family (naturally referring to my own as well as my wife’s side) for supporting me in all those characteristic situations a PhD student gets into over time, and the few rather specific to myself.

Karlsruhe, December 2014

Lukas König

PS. Having little to do with the content of the book, I still cannot leave unmentioned an amazing contributing to a very special day: Thank you, little sister, for an exam celebration cake in the shape of my first computer – including an eatable *Basic* program.

Für Christine

Contents

List of Figures — xiii

List of Tables — xvii

List of Notations — xix

1 Introduction — 1

- 1.1 Evolutionary Robotics and Evolutionary Swarm Robotics — 4
- 1.2 Further Classifications — 5
- 1.3 Challenges of ER — 7
- 1.4 Structure and Major Contributions of the Thesis — 9

2 Robotics, Evolution and Simulation — 13

- 2.1 Evolutionary Training of Robot Controllers — 13
 - 2.1.1 Two Views on Selection in ER and ESR — 16
 - 2.1.2 Classification of Fitness Functions in ER — 18
 - 2.1.3 The Bootstrap Problem — 22
 - 2.1.4 The Reality Gap — 23
 - 2.1.5 Decentralized Online Evolution in ESR — 24
 - 2.1.6 Evolvability, Controller Representation and the Genotype-Phenotype Mapping — 26
 - 2.1.7 Controller Representation — 28
 - 2.1.8 Recombination Operators — 30
 - 2.1.9 Success Prediction in ESR — 30
- 2.2 Agent-based Simulation — 31

3 The Easy Agent Simulation — 35

- 3.1 History of the Easy Agent Simulation Framework — 36
- 3.2 Basic Idea and Architectural Concept — 39
 - 3.2.1 Overview — 39
 - 3.2.2 Preliminaries — 39
 - 3.2.3 Classification of the Architecture — 41
 - 3.2.4 The SPI Architecture from an MVC Perspective — 43
 - 3.2.5 Comparison of the SPI Architecture with State-of-the-Art ABS Frameworks — 46
- 3.3 Implementation of the SPI within the EAS Framework — 48
 - 3.3.1 Overview — 49
 - 3.3.2 Plugins — 49
 - 3.3.3 Master Schedulers — 51

| | | |
|----------|--|------------|
| 3.3.4 | The classes <code>SimulationTime</code> and <code>Wink</code> — | 51 |
| 3.3.5 | The Interface <code>EASRunnable</code> — | 52 |
| 3.3.6 | “Everything is an Agent”: a Philosophical Decision — | 52 |
| 3.3.7 | Running a Simulation — | 54 |
| 3.3.8 | Getting Started — | 56 |
| 3.4 | A Comparative Study and Evaluation of the EAS Framework — | 57 |
| 3.4.1 | Method of Experimentation — | 57 |
| 3.4.2 | Results and Discussion — | 59 |
| 3.5 | Chapter Résumé — | 63 |
| 4 | Evolution Using Finite State Machines — | 65 |
| 4.1 | Theoretical Foundations — | 66 |
| 4.1.1 | Preliminaries — | 67 |
| 4.1.2 | Definition of the MARB Controller Model — | 74 |
| 4.1.3 | Encoding MARBs — | 76 |
| 4.1.4 | Mutation and Hardening — | 83 |
| 4.1.5 | Selection and Recombination — | 90 |
| 4.1.6 | Fitness calculation — | 91 |
| 4.1.7 | The Memory Genome: a Decentralized Elitist Strategy — | 96 |
| 4.1.8 | Fitness Adjustment after Mutation, Recombination and Reactivation of the Memory Genome — | 96 |
| 4.1.9 | The Robot Platforms — | 96 |
| 4.2 | Preliminary Parameter Adjustment using the Example of Collision Avoidance — | 100 |
| 4.2.1 | Specification of Evolutionary Parameters — | 101 |
| 4.2.2 | Method of Experimentation — | 101 |
| 4.2.3 | Evaluation and Discussion — | 103 |
| 4.2.4 | Concluding Remarks — | 106 |
| 4.3 | A Comprehensive Study Using the Examples of Collision Avoidance and Gate Passing — | 107 |
| 4.3.1 | Method of Experimentation — | 108 |
| 4.3.2 | Experimental results — | 111 |
| 4.3.3 | Concluding remarks — | 123 |
| 4.4 | Experiments With Real Robots — | 124 |
| 4.4.1 | Evolutionary Model — | 125 |
| 4.4.2 | Method of Experimentation — | 129 |
| 4.4.3 | Results and Discussion — | 132 |
| 4.4.4 | Concluding Remarks — | 137 |
| 4.5 | Chapter Résumé — | 138 |
| 5 | Evolution and the Genotype-Phenotype Mapping — | 139 |
| 5.1 | Overview of the Presented Approach — | 141 |

| | | |
|-------|--|------------|
| 5.2 | A Completely Evolvable Genotype-Phenotype Mapping — | 143 |
| 5.2.1 | Definition of (complete) evolvability — | 143 |
| 5.2.2 | Properties of ceGPM-based genotypic encodings — | 145 |
| 5.2.3 | The Translator Model MAPT and the Course of Evolution — | 146 |
| 5.2.4 | Genotypic and Phenotypic Spaces — | 156 |
| 5.2.5 | Evolutionary Operators — | 158 |
| 5.3 | Evaluation of the Proposed Evolutionary Model — | 162 |
| 5.3.1 | First Part – Method of Experimentation — | 163 |
| 5.3.2 | First Part – Results and Discussion — | 164 |
| 5.3.3 | Second Part – An Alternate Completely Evolvable Genotype-Phenotype Mapping and its Effects on Evolvability — | 170 |
| 5.3.4 | Second Part – Method of Experimentation — | 176 |
| 5.3.5 | Second Part – Results and Discussion — | 178 |
| 5.3.6 | Third Part – Method of Experimentation — | 181 |
| 5.3.7 | Third Part – Results and Discussion — | 182 |
| 5.4 | Chapter Résumé — | 185 |
| 6 | Data Driven Success Prediction of Evolution in Complex Environments — | 187 |
| 6.1 | Preliminaries — | 189 |
| 6.2 | A Model Capturing Completely Implicit Selection — | 193 |
| 6.2.1 | Two Parents per Reproduction (CIS-2) — | 193 |
| 6.2.2 | Eventually Stable States ($k=2$) — | 195 |
| 6.2.3 | Tournament size k — | 197 |
| 6.2.4 | Eventually Stable States (arbitrary k) — | 200 |
| 6.3 | Extending the CIS Model to Capture Explicit Selection — | 200 |
| 6.4 | Experiments — | 204 |
| 6.4.1 | Evolutionary setup — | 206 |
| 6.4.2 | Experimental Results Using the EIS Model — | 207 |
| 6.4.3 | Remarks on Evolution in the scope of the CIS Model — | 212 |
| 6.5 | Chapter Résumé — | 216 |
| 7 | Conclusion — | 219 |
| | References — | 227 |
| | Index — | 241 |

List of Figures

| | |
|-----------|---|
| Fig. 1.1 | Structure of the thesis — 11 |
| Fig. 2.1 | Classic evolutionary cycle as used in many EC approaches — 14 |
| Fig. 2.2 | Evolutionary process onboard of a robot — 15 |
| Fig. 2.3 | Adaptation of mutation step size in a one-dimensional real-valued search space — 28 |
| Fig. 3.1 | Photography of a swarm of Jasmine IIIp robots — 36 |
| Fig. 3.2 | Two photographs of several Wanda robots — 37 |
| Fig. 3.3 | Live simulation view of an FMG run embedded in the EAS Framework — 38 |
| Fig. 3.4 | Schematic views on the MVC architectural pattern — 44 |
| Fig. 3.5 | Screenshot of a very basic abstract environment in EAS — 45 |
| Fig. 3.6 | Generated pdf of the visualization of a 2D physics environment — 46 |
| Fig. 3.7 | Visualization of a 3D physics environment implemented using the LJGL — 47 |
| Fig. 3.8 | Schematic view on the SPI architecture — 48 |
| Fig. 3.9 | Schematic view of the major classes of EAS including basic methods — 50 |
| Fig. 3.10 | Screenshot of the starter GUI — 55 |
| Fig. 3.11 | Measures of LOC and file count for the three simulations — 60 |
| Fig. 3.12 | Reported time required to implement tasks 1-16 of the Stupid Model — 62 |
| Fig. 4.1 | Example MARBs showing an application of implicit transitions — 71 |
| Fig. 4.2 | Example of the assignment of sensor values to sensor variables — 73 |
| Fig. 4.3 | Schematic view of the encoding of a MARB — 77 |
| Fig. 4.4 | MARB given as an example for the encoding procedure — 79 |
| Fig. 4.5 | Environment used for the evolution of GP behavior — 93 |
| Fig. 4.6 | Photography and sketch of Jasmine IIIp robots in reality and simulation — 98 |
| Fig. 4.7 | Photography and sketch of Wanda robots in reality and simulation — 99 |
| Fig. 4.8 | Hardware layers of a Wanda robot — 100 |
| Fig. 4.9 | Environment for CA — 102 |
| Fig. 4.10 | Distribution of successful runs — 104 |
| Fig. 4.11 | Evolved MARB performing the expected CA behavior — 106 |
| Fig. 4.12 | Evolved MARB performing a circle-driving sub-behavior of the expected CA behavior — 107 |

- Fig. 4.13 Depiction of experimental fields with robots drawn to scale — 109
- Fig. 4.14 Average results at the end of the eight main sets of experiments plotted for the memory genome — 112
- Fig. 4.15 Average fitness during a typical run without memory genome — 113
- Fig. 4.16 Average fitness during a typical run with memory genome — 113
- Fig. 4.17 Average results at the end of the eight main sets of experiments plotted for recombination — 114
- Fig. 4.18 Average fitness of robots in last populations of runs with cloning reproduction — 115
- Fig. 4.19 Average number of successful robots in last populations of runs with cloning reproduction — 116
- Fig. 4.20 Average fitness of robots in last populations of runs with recombination *Cross* — 116
- Fig. 4.21 Average number of successful robots in last populations of runs with recombination *Cross* — 117
- Fig. 4.22 Trajectory of an evolved robot from group 1 doing CA without passing the gate — 119
- Fig. 4.23 Trajectory of an evolved robot from group 1 doing CA in a field with obstacles — 119
- Fig. 4.24 Trajectory produced by a gate passing MARB from group 2 — 120
- Fig. 4.25 Wall Following trajectory produced by a MARB from group 2 — 121
- Fig. 4.26 Trajectory produced by an evolved MARB from group 3 — 122
- Fig. 4.27 MARB avoiding collisions and passing the gate — 123
- Fig. 4.28 Depiction of experimental fields with robots drawn to scale — 127
- Fig. 4.29 Photography of the experimental field for GP — 130
- Fig. 4.30 Comparison of average population fitnesses over experiment time — 132
- Fig. 4.31 Trajectories of an evolved GP behavior traced for 10 minutes — 134
- Fig. 4.32 Simple evolved MARB for GP behavior — 135
-
- Fig. 5.1 Influence of the GPM on the effects of mutation — 141
- Fig. 5.2 Complete evolvability — 144
- Fig. 5.3 Two hand-crafted example automata — 147
- Fig. 5.4 Schematic view of the mutation process onboard of a robot — 149
- Fig. 5.5 Virtual sensors of a MAPT during a translation process — 150
- Fig. 5.6 Example translation of a behavioral gene into a MARB — 154
- Fig. 5.7 Trajectory of an evolved MARB from group 1 (Collision Avoidance) — 165
- Fig. 5.8 Trajectory of an evolved Wall Following MARB from group 2 — 166
- Fig. 5.9 Surprisingly simple evolved Wall Following MARB — 166
- Fig. 5.10 Trajectories of an evolved MARB controlling two robots to pass the gate constantly (group 3) — 167

- Fig. 5.11 Number of gate passages of the three settings — **168**
- Fig. 5.12 Fitness of the three settings — **169**
- Fig. 5.13 Universal translator u' for the MAPT' model — **172**
- Fig. 5.14 Schematic view of the evolutionary process used for studying evolvability — **173**
- Fig. 5.15 Typical fitness curves indicating (top) and not indicating (bottom) evolvability — **175**
- Fig. 5.16 Fields used in the second part of the study — **177**
- Fig. 5.17 Results of category 3 of the second set of experiments — **179**
- Fig. 5.18 Typical MARBs evolved in a setting without behavioral mutations — **180**
- Fig. 5.19 Average fitness over the whole runtime of the first set of runs — **182**
- Fig. 5.20 Average fitness in the last 35,000 steps of the first set of runs — **183**
- Fig. 5.21 Average fitness in the last 35,000 simulation steps of the second set of runs — **184**
- Fig. 5.22 Average fitness in the last 35,000 simulation steps of the second set of runs — **185**
-
- Fig. 6.1 Overview of the intended usage of the success prediction model — **188**
- Fig. 6.2 The four possible situations in a reproduction tournament of the CIS-2 model — **194**
- Fig. 6.3 General form of the transition matrix for the CIS scenario with k parents — **198**
- Fig. 6.4 Expected absorption times for different tournament sizes — **201**
- Fig. 6.5 Probabilities for eventually converging to the superior state $n/0$ in the EIS model — **203**
- Fig. 6.6 Polynomial probability matrices used in the theoretical example — **205**
- Fig. 6.7 The experimentation field with a robot drawn to scale — **206**
- Fig. 6.8 Probabilities for eventually converging to the superior state $30/0$ (uniform selection) — **208**
- Fig. 6.9 Special probability matrix causing “jumps” in the resulting plots — **209**
- Fig. 6.10 Probabilities of converging to the superior stable state (cf. above chart) — **210**
- Fig. 6.11 Probability matrix originating from a decentralized reproduction strategy — **211**
- Fig. 6.12 Probabilities of converging to the superior stable state using decentralized selection — **212**
- Fig. 6.13 Maze environment for the CIS scenario — **214**

- Fig. 6.14 Fitness progression in a CIS run involving fairly complex behavior — **215**
- Fig. 6.15 One of the best MARBs evolved in a CIS run — **216**
- Fig. 7.1 MARB-controlled walk intention detection algorithm in a robotic exoskeleton with crutches — **222**