



Paul Levi
Serge Kernbach (Eds.)

»»COSMOS 7

»»COGNITIVE SYSTEMS MONOGRAPHS

Symbiotic Multi-Robot Organisms

Reliability, Adaptability, Evolution

 Springer

Cognitive Systems Monographs

Volume 7

Editors: Rüdiger Dillmann · Yoshihiko Nakamura · Stefan Schaal · David Vernon

Paul Levi and Serge Kernbach (Eds.)

Symbiotic Multi-Robot Organisms

Reliability, Adaptability, Evolution

 Springer

Rüdiger Dillmann, University of Karlsruhe, Faculty of Informatics, Institute of Anthropomatics, Humanoids and Intelligence Systems Laboratories, Kaiserstr. 12, 76131 Karlsruhe, Germany

Yoshihiko Nakamura, Tokyo University Fac. Engineering, Dept. Mechano-Informatics, 7-3-1 Hongo, Bukyo-ku Tokyo, 113-8656, Japan

Stefan Schaal, University of Southern California, Department Computer Science, Computational Learning & Motor Control Lab., Los Angeles, CA 90089-2905, USA

David Vernon, Khalifa University Department of Computer Engineering, PO Box 573, Sharjah, United Arab Emirates

Editors

Dr. Paul Levi

Professor of Computer Science
IPVS, Universität Stuttgart
Universitätsstr. 38
70569 Stuttgart
Germany
levi@ipvs.uni-stuttgart.de

Dr. Serge Kernbach

IPVS, Universität Stuttgart
Universitätsstr. 38
70569 Stuttgart
Germany
serge.kernbach@ipvs.uni-stuttgart.de

ISBN 978-3-642-11691-9

e-ISBN 978-3-642-11692-6

DOI 10.1007/978-3-642-11692-6

Cognitive Systems Monographs

ISSN 1867-4925

Library of Congress Control Number: 2010925112

© 2010 Springer-Verlag Berlin Heidelberg

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer. Violations are liable for prosecution under the German Copyright Law.

The use of general descriptive names, registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Typeset & Cover Design: Scientific Publishing Services Pvt. Ltd., Chennai, India.

Printed on acid-free paper

5 4 3 2 1 0

springer.com

Foreword

It is our pleasure to contribute the foreword to this book on symbiotic multi-robot organisms, which is largely based on the scientific findings and explorations of two major EU research projects, *Symbion* and *Replicator*, funded under the Seventh Framework Programme for Research and Technological development (FP7)¹. FP7 emphasises consortia of European partners, trans-national collaboration, open coordination, flexibility and excellence of research and plays a leading role in multidisciplinary research and cooperative activities in Europe and beyond. Its impact is major in terms of integrating and structuring research communities across national borders to achieve a critical mass, providing the leverage for high-potential fields to take off, and encouraging healthy competition at European level while avoiding unnecessary duplication of research capacities. Research proposals are evaluated through a demanding peer-review process and only the best are selected to be funded by the European Commission (EC). The Information and Communication Technologies (ICT) theme has set out a number of challenges within this context, which cover topics such as cognitive systems, modular robotics, adaptive systems and societies of artefacts.

- **Symbion** was selected following the Call “Pervasive Adaptation” of the “Future and Emerging Technologies (FET)” programme area². It started on 1 February 2008 and will run for 5 years. FET Proactive addresses evolutionary and revolutionary approaches through multidisciplinary cooperation and investigates new future technology options in response to emerging societal and industrial needs and identifies new drivers for research.
- **Replicator** was selected under the “Cognitive Systems and Robotics” programme area³. It started on 1 March 2008 and will also run for 5 years.

¹ The views expressed in this foreword are the sole responsibility of the authors and in no way represent the view of the European Commission and its services.

² http://cordis.europa.eu/fp7/ict/fet-proactive/home_en.html

³ <http://www.cognitivesystems.eu>

The “Cognitive Systems and Robotics” challenge supports research on the engineering of artificial cognitive systems and in particular endowing robots with cognitive and other advanced capabilities.

These projects address major challenges for the robotics of the future that were identified during intensive consultations with leading scientists. Robots will have to harness and interpret information (e.g., speech, images or sensor data), carry out useful tasks (e.g. manipulation and grasping, exploration and navigation, monitoring and control, situation assessment, communication and interaction) and pursue immediate or long-term goals, autonomously or in cooperation with people or other robots. Moreover future robots will have to be:

- **Reliable and robust**, able to operate in adverse conditions for a long period of time without frequent or major maintenance.
- **Learning**, able to improve their capabilities through individual or social interactions with their environment, people or other robots.
- **Adaptable**, able to operate autonomously in loosely-structured, unpredictable, highly-dynamic and open environments, technological and user contexts.
- **Modular**, able, on their own initiative, to operate as a larger system to tackle problems or carry out tasks they would not be able to tackle or carry out individually.
- **Collaborative and social**, able, on their own initiative, to collaborate in a natural way with people or other robots, and to adapt to each others and to changing needs.
- **Evolvable**, able to elaborate strategies operating at different speeds and time scales, from the short-term development of specific skills to the long-term evolution into different species.

To realise the potential of this exciting field, it is crucial to stimulate contributions from and to create synergies between different disciplines, including robotics, cognitive systems, adaptive systems, the social sciences and biology. Symbrion and Replicator are examples of such efforts. Both projects work towards individual robots that are capable of adapting, reconfiguring and self-assembling into large artificial organisms. They will develop novel principles underlying these robotic organisms, such as self-configuration, self-adjustment and self-learning. Furthermore, they share a common platform to avoid duplication in this area.

- **Replicator** aims at developing small, autonomous reliable, highly capable and sensor-rich (laser, camera, RFID, localisation) robots which are able to self-assemble into large artificial organisms on their own initiative. The bio-inspired evolutionary approach and evolvable hardware structure will enable the robotic organisms to emerge new functionalities, to develop their own cognitive and control structures and, finally, to work autonomously in uncertain situations within open-ended or even hazardous, environments.

- **Symbrion** focuses on evolutionary and bio-mimicking approaches to explore biological concepts with robot populations (e.g., artificial evolution, pervasive evolveability, artificial immunology, genetic self-reprogramming, virtual sexuality). It places more emphasis on the genomic framework and genetic learning based on feedback from the environment. Accordingly, it uses large computation resources on the platform and more emphasis is put on collective behaviours and on the assembly into organisms.

Considering both projects together and their respective funding, 5.4 M€ for Replicator and 5.3 M€ for Symbrion (with a 0.5 M€ extension under negotiation), this is one of the largest combined grants ever in collaborative and evolutionary robotics. In this context the research community, the European Commission and both consortia recognise the crucial importance of identifying key underlying scientific questions, deriving scientific and technological priorities from these goals and using them to obtain important and highly-visible outcomes. Apart from the scientific impact, it is likely that both projects will contribute to longer-term applications in various domains, such as surveillance and intervention, exploration and inspection, and search and rescue.

We hope that the readers will enjoy this book as much as we did, and wish both teams success in achieving their ambitious goals.

Olivier Da Costa
(Replicator Project Officer, DG InfSo “Cognitive Systems, Interaction,
Robotics”)

Wide Hogenhout
(Symbrion Project Officer, DG InfSo “Future and Emerging Technologies
(FET) Proactive”)

Acknowledgements

The investigation of artificial multicellularity and the development of robot organisms was only possible by the support of the European Commission, Directorate-General Information Society & Media over several years within the 7th Framework Program in the field of “Cognitive Systems, Interaction, Robotics” and “Future and Emerging Technologies”. The Strategic Research Agenda, Vision and Challenges are discussed with many experts from robotics, biology, genetics, evolutionary computations, machine learning. Considerable amount of preparatory works has been done within the I-Swarm, Swarmrobot, GOLEM, NEW TIES, Artificial Culture, LEURRE, SuperBot, Swarm-bots, HYDRA, CEBOT projects as well as discussed within the coordinated actions PerAda (Pervasive Adaptation Research Network) and euCognition (EUCogII – European Network for the Advancement of Artificial Cognitive Systems, Interaction and Robotics), which finally defined the field and the road to implementation. Organizers of the special sections and workshops during CEC, IROS, ICRA, GECCO, ICT, FET and several IEEE conferences gave us a great opportunity to present the ideas to scientific community and to collect a valuable feedback. We are grateful to our multiple reviewers for very intensive and fruitful remarks and corrections as well as to project officers whose continuous support essentially contributed to advances and progress of the research and development.

Ideas, experiments and implementations, described in this book were also impossible without a huge amount of effort and time, invested by young and senior researchers of our consortiums. The work of the last few years was of great strength and we are thankful to the consortiums for readiness to contribute, continuous availability and excellent motivation. This finally allowed formulating the ambitious goals towards possible future ways of the collective robotics.

Contents

Introduction	1
1 Concepts of Symbiotic Robot Organisms	5
1.1 From Robot Swarm to Artificial Organisms: Self-organization of Structures, Adaptivity and Self-development	5
1.1.1 Mono- and Multi- functional Artificial Self-organization	7
1.1.2 Collective Robotics: Problem of Structures	11
1.1.3 Adaptability and Self-development	14
1.1.4 Artificial Symbiotic Systems: Perspectives and Challenges	21
1.2 Towards a Synergetic Quantum Field Theory for Evolutionary, Symbiotic Multi-Robotics	25
1.2.1 Cooperative (Coherent) Operations between Fermionic Units	28
1.2.2 Individual Contributions of the Eigenanteile	36
1.2.3 Separate Perturbations of the Eigenanteile	40
1.2.4 Coupling of the Disturbed Eigenanteil Equations	42
1.2.5 Information Model and Interactions of Structured Components	45
1.3 Functional and Reliability Modelling of Swarm Robotic Systems	54
1.3.1 Macroscopic Probabilistic Modelling in Swarm Robotics	54
1.3.2 Reliability Modelling of Swarm Robotic Systems	65
1.3.3 Concluding Discussion	76

2	Heterogeneous Multi-Robot Systems	79
2.1	Reconfigurable Heterogeneous Mechanical Modules	79
2.1.1	A Heterogeneous Approach in Modular Robotics	80
2.1.2	Integration and Miniaturization	82
2.1.3	Locomotion Mechanisms	84
2.1.4	Docking Mechanisms and Strategies	86
2.1.5	Mechanical Degrees of Freedoms: Actuation for the Individual Robot and for the Organism	88
2.1.6	Tool Module: Active Wheel	88
2.1.7	Summary of the Three Robotic Platforms	91
2.2	Computation, Distributed Sensing and Communication	92
2.2.1	Electronic Architectures in Related Works	93
2.2.2	General Hardware Architecture in SYMBRION/REPLICATOR	94
2.2.3	General Sensor Capabilities	97
2.2.4	Vision and IR-Based Perception	100
2.2.5	Triangulation Laser Range Sensor for Obstacle Detection and Interpretation of Basic Geometric Features	105
2.2.6	Powerful Wireless Communication and 3D Real Time Localisation Systems	107
2.2.7	Integration Issues	113
2.3	Energy Autonomy and Energy Harvesting in Reconfigurable Swarm Robotics	114
2.3.1	Energy Autonomy	115
2.3.2	Energy Harvesting	116
2.3.3	Energy Trophallaxis	119
2.3.4	Energy Sharing within a Robot Organism	121
2.3.5	Energy Management	122
2.4	Modular Robot Simulation	133
2.4.1	Simulation Environments	134
2.4.2	The Symbricator3D Simulation Environment	137
2.4.3	Showcase: The Dynamics Predictor	149
2.4.4	Conclusion and Future Work	162
3	Cognitive Approach in Artificial Organisms	165
3.1	Cognitive World Modeling	165
3.1.1	Methodology	166
3.1.2	Spatial World Modeling	166
3.1.3	Evolution Map	167
3.1.4	Map	169
3.1.5	Jockeys	170
3.1.6	Reasoning	172
3.1.7	Executor	173

3.1.8	Porting the EMa onto a Robot	174
3.1.9	EMa Care-Taking Procedures	175
3.1.10	Physical Layout	176
3.1.11	Logical Layout and Communication	177
3.1.12	Experiments	179
3.1.13	Functional World Modelling	180
3.2	Emergent Cognitive Sensor Fusion	183
3.2.1	Scenarios	185
3.2.2	Towards Embodied and Emergent Cognition	188
3.2.3	Sensor Fusion Model	192
3.3	Application of Embodied Cognition to the Development of Artificial Organisms	202
3.3.1	Natural vs. Artificial Systems: Collectivity and Adaptability in Inanimated Nature	203
3.3.2	Definition of Information and Knowledge Related to Restrictions	211
3.3.3	Collectivity and Adaptability in Animated Nature	219
3.3.4	Information Based Learning to Develop and Maintain Artificial Organisms	221
4	Adaptive Control Mechanisms	229
4.1	General Controller Framework	229
4.1.1	Controller Framework in SYMBRION/REPLICATOR	229
4.1.2	Bio-inspiration for the Structure of Artificial Genome	232
4.1.3	Action Selection Mechanism	234
4.1.4	Overview of Different Control Mechanisms	235
4.2	Hormone-Based Control for Multi-modular Robotics	240
4.2.1	Micro-organisms' Cell Signals and Hormones as Source of Inspiration	241
4.2.2	Related Work	246
4.2.3	Artificial Homeostatic Hormone System (AHHS)	247
4.2.4	Encoding an AHHS into a Genome	249
4.2.5	Self-organised Compartmentalisation	250
4.2.6	Evolutionary Adaptation	255
4.2.7	Single Robots	256
4.2.8	Forming Robot Organisms	257
4.2.9	Locomotion of Robot Organisms	259
4.2.10	Feedbacks	261
4.2.11	Conclusion	262
4.3	Evolving Artificial Neural Networks and Artificial Embryology	263

4.3.1	Shaping of ANN in Literature	264
4.3.2	Overview over Section	266
4.3.3	Concept of Adapting Virtual Embryogenesis for Controller Development	266
4.3.4	Diffusion Processes	267
4.3.5	Genetics and Cellular Behaviour	268
4.3.6	Simulated Physics	269
4.3.7	Cell Specialisation	270
4.3.8	Linkage	270
4.3.9	Depicting Genetic Structures and Feedbacks	272
4.3.10	Stable Growth due to Feedbacks in Genetic Structure	275
4.3.11	Developing Complex Shapes	276
4.3.12	The Growth of Neurons	277
4.3.13	Translation	278
4.3.14	Usability of Virtual Embryogenesis in the Context of Artificial Evolution for Shaping Artificial Neural Networks and Robot Controllers	279
4.3.15	Subsumption of Section	281
4.4	An Artificial Immune System for Robot Organisms	282
4.4.1	A Biological and Engineering Perspective	283
4.4.2	An Immune-inspired Architecture for Fault Tolerance in Swarm and Collective Robotic Systems	290
4.4.3	Innate Layer	293
4.4.4	Adaptive Layer	294
4.4.5	Summary	305
4.5	Structural Self-organized Control	306
4.5.1	Representation of Structures	308
4.5.2	Compact Representation: The Topology Generator	313
4.5.3	Scalability of Structures and Appearing Constraints	314
4.5.4	Morphogenesis as an Optimal Decision Problem	317
4.5.5	Self-organized Morphogenesis	322
4.5.6	Collective Memory and Further Points	325
4.6	Kinematics and Dynamics for Robot Organisms	326
4.6.1	Modeling of Multi-robot Organisms	328
4.6.2	Inverse Kinematics	332
4.6.3	Dynamics	333
4.6.4	Computational Analysis	335
4.6.5	Conclusion	336

5	Learning, Artificial Evolution and Cultural Aspects of Symbiotic Robotics	337
5.1	Machine Learning for Autonomous Robotics	337
5.1.1	Related Work	338
5.1.2	Challenges for ML-Based Robotics	347
5.1.3	The WOALA Scheme	349
5.1.4	First Experiments with WOALA	353
5.1.5	Discussion and Perspectives	361
5.2	Embodied, On-Line, On-Board Evolution for Autonomous Robotics	362
5.2.1	Controllers, Genomes, Learning, and Evolution . . .	363
5.2.2	Classification of Approaches to Evolving Robot Controllers	364
5.2.3	The Classical Off-Line Approach Based on a Master EA	368
5.2.4	On-Line Approaches	369
5.2.5	Testing Encapsulated Evolutionary Approaches . . .	372
5.2.6	Conclusions and Future Work	382
5.3	Artificial Sexuality and Reproduction of Robot Organisms	384
5.3.1	The Role of Sexuality for Robots	385
5.3.2	Artificial Reproduction	388
5.3.3	Implementation of Artificial Sexuality on Real Robots	390
5.3.4	Evolutionary Engineering	392
5.3.5	Evolution of Multicellular Organisms	397
5.3.6	Sex and Reproduction of Symbiotic Robots	399
5.3.7	Conclusion	403
5.4	Self-learning Behavior of Virus-Like Artificial Organisms	403
5.4.1	Effectiveness of Evolutionary Optimization for Genetic Cloud	405
5.4.2	Interaction between Evolution and Learning in an Evolutionary Process	412
5.4.3	Evolutionary Emergence of a Cooperation between Agents	418
5.4.4	Discovering of Chains of Actions by Self-learning Agents	421
5.4.5	Virus-Like Organisms: New Adaptive Paradigm?	424
5.5	Towards the Emergence of Artificial Culture in Collective Robotic Systems	425
5.5.1	Project Aims	425
5.5.2	The Artificial Culture Laboratory	426

5.5.3	The Challenges and the Case for an Emerging Robot Culture	428
5.5.4	Robot Memes and Meme Tracking	430
5.5.5	Concluding Remarks	433
Final Conclusions		435
References		437
Index		467

List of Contributors

A.E. Eiben

Faculty of Sciences, Department of
Computer Science,
VU University Amsterdam,
De Boelelaan 1081a,
1081 HV Amsterdam,
The Netherlands
gusz@few.vu.nl

Amelia Ritahani Ismail

Department of Computer Science,
University of York, Heslington, York,
YO10 5DD. UK
ritahani@cs.york.ac.uk

Alan F.T. Winfield

Bristol Robotics Laboratory (BRL),
University of the West of England,
Bristol (UWE), Coldharbour Lane,
Frenchay, Bristol BS16 1QY,
England
alan.winfield@uwe.ac.uk

Alfons H. Salden

Almende B.V., Westerstraat 50, 3016
DJ Rotterdam, The Netherlands
alfons@almende.com

Andy Tyrrell

Department of Electronics,

University of York, Heslington,
York, YO10 5DD, UK
amt@ohm.york.ac.uk

Anne C. van Rossum

Almende B.V., Westerstraat 50,
3016 DJ Rotterdam,
The Netherlands
anne@almende.com

Arianna Menciassi

Polo Sant'Anna Valdera, Scuola
Superiore Sant'Anna, Viale Rinaldo
Piaggio 34, 56025 Pontedera (PI),
Italy
arianna.menciassi@sssup.it

Christoph Hösler

Institute for Evolution and Ecology,
University of Tübingen, Auf der
Morgenstelle 28, 72076 Tübingen,
Germany
hoesler@asoem.org

Christopher Schwarzer

Institute for Evolution and Ecology,
University of Tübingen, Auf der
Morgenstelle 28, 72076 Tübingen,
Germany
christopher.schwarzer@
uni-tuebingen.de