

Cognitive Systems Monographs

Volume 11

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

David Vernon, Claes von Hofsten,
and Luciano Fadiga

A Roadmap for Cognitive Development in Humanoid Robots

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, Department of Robotics, Brain and Cognitive Sciences, Italian Institute of Technology, Genoa, Italy

Authors

David Vernon
Department of Robotics, Brain and
Cognitive Sciences
Italian Institute of Technology
Genoa
Italy
E-mail: david@vernon.eu

Luciano Fadiga
Section of Human Physiology
University of Ferrara
Italy
E-mail: fdl@unife.it

and

Claes von Hofsten
Psykologisk institutt
Universitetet i Oslo
Oslo
Norway
E-mail: claes.von_hofsten@psyk.uu.se

Department of Robotics, Brain and
Cognitive Sciences
Italian Institute of Technology
Genoa

ISBN 978-3-642-16903-8

e-ISBN 978-3-642-16904-5

DOI 10.1007/978-3-642-16904-5

Cognitive Systems Monographs

ISSN 1867-4925

Library of Congress Control Number: 2010938643

© 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

Preface

The work described in this book is founded on the premise that (a) cognition is the process by which an autonomous self-governing agent acts effectively in the world in which it is embedded, that (b) the dual purpose of cognition is to increase the agent's repertoire of effective actions and its power to anticipate the need for and outcome of future actions, and that (c) development plays an essential role in the realization of these cognitive capabilities.

Cognitive agents act in their world, typically with incomplete, uncertain, and time-varying sensory data. The chief purpose of cognition is to enable the selection of actions that are appropriate to the circumstances. However, the latencies inherent in the neural processing of sense data are often too great to allow effective action. Consequently, a cognitive agent must anticipate future events so that it can prepare the actions it may need to take. Furthermore, the world in which the agent is embedded is unconstrained so that it is not possible to predict all the circumstances it will experience and, hence, it is not possible to encapsulate *a priori* all the knowledge required to deal successfully with them. A cognitive agent then must not only be able to anticipate but it must also be able to learn and adapt, progressively increasing its space of possible actions as well as the time horizon of its prospective capabilities. In other words, a cognitive agent must develop.

There are many implications of this stance. First, there must be some starting point for development — some phylogeny — both in terms of the initial capabilities and in terms of the mechanisms which support the developmental process. Second, there must be a developmental path — an ontogeny — which the agent follows in its attempts to develop an increased degree of prospection and a larger space of action. This involves several stages, from coordination of eye-gaze, head attitude, and hand placement when reaching, through to more complex exploratory use of action. This is typically achieved by dexterous manipulation of the environment to learn the affordances of objects in the context of one's own developing capabilities. Third, since cognitive agents rarely operate in isolation and since the world with which they interact typically includes other cognitive agents, there is the question of how a cognitive

agent can share with other agents the knowledge it has learned. Since what an agent knows is based on its history of experiences in the world, the meaning of any shared knowledge depends on a common mode of experiencing the world. In turn, this implies that the shared knowledge is predicated upon the agents having a common morphology and, in the case of human-robot interaction, a common humanoid form.

The roadmap set out in this book targets specifically the development of cognitive capabilities in humanoid robots. It identifies the necessary and hopefully sufficient conditions that must exist to allow this development. It has been created by bringing together insights from four areas: enactive cognitive science, developmental psychology, neurophysiology, and cognitive modelling. Thus, the roadmap builds upon what is known about the development of natural cognitive systems and what is known about computational modelling of artificial cognitive agents. In doing so, it identifies the essential principles of a system that can develop cognitive capabilities and it shows how these principles have been applied to the state-of-the-art humanoid robot: the iCub.

The book is organized as follows. Chapter 1 presents a conceptual framework that forms the foundation of the book. It identifies the broad stance taken on cognitive systems — emergent embodied systems that develop cognitive skills as a result of their action in the world — and it draws out explicitly the consequences of adopting this stance. Chapter 2 begins by discussing the importance of action as the organizing principle in cognitive behaviour, a theme that will recur repeatedly throughout the book. It then addresses the phylogeny of human infants and, in particular, it considers the innate capabilities of pre-natal infants and how these develop before and just after birth. Chapter 3 then details how these capabilities develop in the first couple of years of life, focussing on the interdependence of perception and action. In doing so, it develops the second recurrent theme of the book: the central role of prospective capabilities in cognition. Chapter 4 explores the neurophysiology of perception and action, delving more deeply into the way that the interdependency of perception and action is manifested in the primate brain. While Chapters 2 – 4 provide the biological inspiration for the design of an entity that can develop cognitive capabilities, Chapter 5 surveys recent attempts at building artificial cognitive systems, focussing on cognitive architectures as the basis for development. Chapter 6 then presents a complete roadmap that uses the phylogeny and ontogeny of natural systems as well as insights gained from computational models and cognitive architectures to define the innate capabilities with which the humanoid robot must be equipped so that it is capable of ontogenetic development. The roadmap includes a series of scenarios that can be used to drive the robot’s developmental progress. Chapter 7 provides an overview of the iCub humanoid robot and it describes the use of the the roadmap in the realization of the iCub’s own cognitive architecture. Chapter 8 concludes by setting out an agenda for future research and

addressing the most pressing issues that will advance our understanding of cognitive systems, artificial and natural.

Dublin, Uppsala, and Ferrara
August 2010

David Vernon
Claes von Hofsten
Luciano Fadiga

Acknowledgements

This book is based on the results of the RobotCub research project, the goal of which was to develop the iCub: an open and widely-adopted humanoid robot for cognitive systems research. This project was supported by the European Commission, Project IST-004370, under Strategic Objective 2.3.2.4: Cognitive Systems and we gratefully acknowledge the funding that made this research possible.

In particular, we would like to thank Hans-Georg Stork, European Commission, for his support, insight, and unfailing belief in the project.

We would also like to acknowledge the contributions made by the five reviewers of the project over its five-and-a-half year lifetime: Andreas Birk, Joanna Bryson, Bob Damber, Peter Ford Dominey, and Raul Rojas. Their collective suggestions helped greatly in navigating uncharted waters.

We are indebted to the members of the project's International Advisory Board — Rodney Brooks, MIT, Gordon Cheng, Technical University of Munich, Jürgen Konczak, University of Minnesota, Hideki Kozima, CRL, and Yasuo Kuniyoshi, University of Tokyo — for providing valuable advice and moral support.

Over one hundred people were involved in the creation of the iCub and it is impossible to acknowledge the contribution each made to the work that is described in this book. However, certain key individuals in each of the eleven institutes that participated in the research played a pivotal role in bringing the five year project to a successful conclusion. It is a pleasure to acknowledge their contributions.

Giulio Sandini, Italian Institute of Technology and University of Genoa, was the mastermind behind the project and he was the first to see the need for a common humanoid robot platform to support research in embodied cognitive systems and the benefits of adopting an open-systems policy for software and hardware development.

Giorgio Metta, Italian Institute of Technology and University of Genoa, inspired many of the design choices and provided leadership, guidance, and a level of commitment to the project that was crucial for its success.

Paul Fitzpatrick, Lorenzo Natale and Francesco Nori, Italian Institute of Technology and University of Genoa, together formed an indispensable team whose wide-ranging contributions to the software and hardware formed the critical core of the iCub.

José Santos-Victor and Alex Bernardino, IST Lisbon, set the benchmark early on with their design of the iCub head and their work on learning affordances, computational attention, gaze control, and hand-eye coordination.

Francesco Becchi, Telerobot S.r.l., provided the industry-strength know-how which ensured that mechanical components of the iCub were designed, fabricated, assembled, and tested to professional standards.

Rolf Pfeifer, University of Zurich, provided inspiration for the tight relationship between a system's embodiment and its cognitive behaviour, a relationship that manifests itself in several ways in the the design of the iCub.

Kerstin Rosander, University of Uppsala, was instrumental in keeping the work on developmental psychology in focus and on track.

Laila Craighero, University of Ferrara, provided many of the key insights from neurophysiology which guided our models of cognitive development.

Paolo Dario and Cecilia Laschi, Scuola S. Anna, Pisa contributed expertise in robot control systems for visual servo control and tracking.

Kerstin Dautenhahn, Chrystopher Nehaniv, University of Hertfordshire, provided guidance on social human-robot interaction.

Darwin Caldwell and Nikos Tsagarakis, Italian Institute of Technology and University of Sheffield, were responsible of the success of the design of the iCub's torso and legs.

Aude Billard and Auke Ijspeert, Ecole Polytechnique Federal de Lausanne, developed the software for imitation-based learning and gait control, respectively.

To the countless other people we haven't named — Commission officers, technicians, professors, Ph.D. and M.Sc. students, research assistants, office administrators, post-docs — a heart-felt thank you. This book reflects only a small part of the RobotCub project but it wouldn't have been possible without the collective effort of everyone involved in creating the iCub.

Finally, a big thank you to Keelin for her painstaking work proofreading the manuscript.

Contents

| | | |
|----------|---|-----------|
| 1 | A Conceptual Framework for Developmental Cognitive Systems | 1 |
| 1.1 | Introduction | 1 |
| 1.2 | Cognition | 2 |
| 1.3 | Enaction | 3 |
| 1.3.1 | Enaction and Development | 5 |
| 1.3.2 | Enaction and Knowledge | 7 |
| 1.3.3 | Phylogeny and Ontogeny: The Complementarity of Structural Determination and Development | 8 |
| 1.4 | Embodiment: The Requirements and Consequences of Action | 8 |
| 1.5 | Challenges | 10 |
| 1.6 | Summary | 11 |
| 2 | Pre-natal Development and Core Abilities | 13 |
| 2.1 | Action as the Organizing Principle in Cognitive Behaviour | 13 |
| 2.2 | Prenatal Development | 15 |
| 2.2.1 | Morphological Pre-structuring | 16 |
| 2.2.2 | Pre-structuring of the Motor System | 16 |
| 2.2.3 | Pre-structuring of the Perceptual System | 18 |
| 2.2.4 | Forming Functional Systems | 20 |
| 2.3 | Core Abilities | 20 |
| 2.3.1 | Core Knowledge | 20 |
| 2.3.2 | Core Motives | 23 |
| 2.4 | Summary | 24 |
| 2.4.1 | Actions | 24 |
| 2.4.2 | Prenatal Development | 25 |
| 2.4.3 | Core Abilities | 26 |

| | | |
|----------|--|-----------|
| 3 | The Development of Cognitive Capabilities in Infants . . . | 29 |
| 3.1 | The Development of Perception | 29 |
| 3.2 | Visual Development | 30 |
| 3.2.1 | Space Perception | 32 |
| 3.2.2 | Object Perception | 34 |
| 3.3 | Acquiring Predictive Control | 35 |
| 3.3.1 | Development of Posture and Locomotion | 35 |
| 3.3.2 | Development of Looking | 40 |
| 3.3.3 | Development of Reaching and Manipulation | 44 |
| 3.3.4 | Development of Social Abilities | 54 |
| 3.4 | Summary | 57 |
| 3.4.1 | The Basis for Development | 57 |
| 3.4.2 | Visual Processing | 58 |
| 3.4.3 | Posture | 59 |
| 3.4.4 | Gaze | 60 |
| 3.4.5 | Reaching and Grasping | 61 |
| 3.4.6 | Manipulation | 63 |
| 3.4.7 | Social Abilities | 63 |
| 4 | What Neurophysiology Teaches Us About Perception and Action | 65 |
| 4.1 | The Premotor Cortex of Primates Encodes Actions and Not Movements | 65 |
| 4.2 | The System for Grasping | 68 |
| 4.3 | The Distributed Perception of Space | 70 |
| 4.4 | Perception Depends on Action | 72 |
| 4.5 | Action and Selective Attention | 73 |
| 4.6 | Structured Interactions | 76 |
| 4.7 | Summary | 76 |
| 4.7.1 | Grasping | 77 |
| 4.7.2 | Spatial Perception | 77 |
| 4.7.3 | Perception-Action Dependency | 78 |
| 4.7.4 | Structured Interactions | 79 |
| 4.7.5 | Selective Attention | 79 |
| 5 | Computational Models of Cognition | 81 |
| 5.1 | The Three Paradigms of Cognition | 81 |
| 5.1.1 | The Cognitivist Paradigm | 85 |
| 5.1.2 | The Emergent Paradigm | 86 |
| 5.1.3 | The Hybrid Paradigm | 86 |
| 5.1.4 | Relative Strengths | 87 |
| 5.2 | Cognitive Architectures | 89 |
| 5.2.1 | The Cognitivist Perspective on Cognitive Architectures | 89 |

| | | |
|----------|---|------------|
| 5.2.2 | The Emergent Perspective on Cognitive Architectures | 90 |
| 5.2.3 | Desirable Characteristics of a Cognitive Architecture | 91 |
| 5.2.4 | A Survey of Cognitive Architectures | 95 |
| 5.3 | Summary | 98 |
| 6 | A Research Roadmap | 101 |
| 6.1 | Phylogeny | 103 |
| 6.1.1 | Guidelines from Enaction | 103 |
| 6.1.2 | Guidelines from Developmental Psychology | 103 |
| 6.1.3 | Guidelines from Neurophysiology | 105 |
| 6.1.4 | Guidelines from Computational Modelling | 105 |
| 6.1.5 | A Summary of the Phylogenetic Guidelines for the Development of Cognition in Artificial Systems | 108 |
| 6.2 | Ontogeny | 110 |
| 6.2.1 | Guidelines from Developmental Psychology | 110 |
| 6.2.2 | Scenarios for Development | 111 |
| 6.2.3 | Scripted Exercises | 114 |
| 7 | The iCub Cognitive Architecture | 121 |
| 7.1 | The iCub Humanoid Robot | 121 |
| 7.1.1 | The iCub Mechatronics | 122 |
| 7.1.2 | The iCub Middleware | 124 |
| 7.2 | The iCub Cognitive Architecture | 125 |
| 7.2.1 | Embodiment: The iCub Interface | 127 |
| 7.2.2 | Perception | 130 |
| 7.2.3 | Action | 134 |
| 7.2.4 | Anticipation & Adaptation | 138 |
| 7.2.5 | Motivation: Affective State | 141 |
| 7.2.6 | Autonomy: Action Selection | 142 |
| 7.2.7 | Software Implementation | 142 |
| 7.3 | The iCub Cognitive Architecture vs. the Roadmap Guidelines | 144 |
| 7.3.1 | Embodiment | 144 |
| 7.3.2 | Perception | 145 |
| 7.3.3 | Action | 148 |
| 7.3.4 | Anticipation | 149 |
| 7.3.5 | Adaptation | 150 |
| 7.3.6 | Motivation | 151 |
| 7.3.7 | Autonomy | 151 |
| 7.4 | Summary | 153 |

| | | |
|----------|---|-----|
| 8 | Conclusion | 155 |
| 8.1 | Multiple Mechanisms for Anticipation | 155 |
| 8.2 | Prediction, Reconstruction, and Action: Learning Affordances | 156 |
| 8.3 | Object Representation | 156 |
| 8.4 | Multi-modal and Hierarchical Episodic Memory | 157 |
| 8.5 | Generalization and Model Generation | 157 |
| 8.6 | Homeostasis and Development | 158 |
| A | Catalogue of Cognitive Architectures | 159 |
| A.1 | Cognitivist Cognitive Architectures | 160 |
| A.1.1 | The Soar Cognitive Architecture | 160 |
| A.1.2 | EPIC — Executive Process Interactive Control | 161 |
| A.1.3 | ACT-R — Adaptive Control of Thought - Rational | 162 |
| A.1.4 | The ICARUS Cognitive Architecture | 165 |
| A.1.5 | ADAPT — A Cognitive Architecture for Robotics | 167 |
| A.1.6 | The GLAIR Cognitive Architecture | 168 |
| A.1.7 | CoSy Architecture Schema | 170 |
| A.2 | Emergent Cognitive Architectures | 174 |
| A.2.1 | Autonomous Agent Robotics | 174 |
| A.2.2 | A Global Workspace Cognitive Architecture | 175 |
| A.2.3 | Self-directed Anticipative Learning | 178 |
| A.2.4 | A Self-Affecting Self-Aware (SASE) Cognitive Architecture | 179 |
| A.2.5 | Darwin: Neuromimetic Robotic Brain-Based Devices | 181 |
| A.2.6 | The Cognitive-Affective Architecture | 183 |
| A.3 | Hybrid Cognitive Architectures | 186 |
| A.3.1 | A Humanoid Robot Cognitive Architecture | 186 |
| A.3.2 | The Cerebus Architecture | 187 |
| A.3.3 | Cog: Theory of Mind | 189 |
| A.3.4 | Kismet | 190 |
| A.3.5 | The LIDA Cognitive Architecture | 192 |
| A.3.6 | The CLARION Cognitive Architecture | 194 |
| A.3.7 | The PACO-PLUS Cognitive Architecture | 196 |
| | References | 199 |
| | Index | 219 |