

智能系统

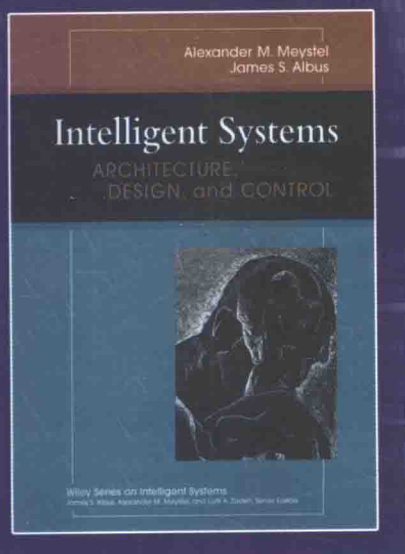
——结构、设计与控制

Intelligent Systems:

Architecture, Design and Control

英文版

[美] Alexander M. Meystel 著
James S. Albus



电子工业出版社

Publishing House of Electronics Industry

<http://www.phei.com.cn>

国外计算机科学教材系列

智能系统

—— 结构、设计与控制

(英文版)

Intelligent Systems

Architecture, Design, and Control

[美] Alexander M. Meystel 著
James S. Albus

电子工业出版社
Publishing House of Electronics Industry
北京 · BEIJING

内 容 简 介

虽然智能是一个较难理解的概念,但在生物学和人工智能系统领域,对智能机制和功能的研究却在不断扩大。本书介绍了智能系统的最初的模型,并把多种来源的知识综合到一起,开发了一种理论,这种理论可以用来分析从经济到集成制造领域的所有复杂系统。本书的重点在于把智能作为一种多解决方案中的计算现象,希望能够影响在智能领域内的未来研究和方向。它是科学家、工程师和希望探索当代理论和计算智能工具的宝贵资源。

本书适用于大学研究生、科学家、工程技术人员和对智能研究感兴趣的人士。

Alexander M. Meystel, James S. Albus: Intelligent Systems: Architecture, Design, and Control.

ISBN 0-471-19374-7. Copyright © 2002.

Authorized reprint of the edition published by John Wiley & Sons, Inc., New York, Chichester, Weinheim, Singapore, Brisbane, Toronto. No part of this book may be reproduced in any form without the written permission of John Wiley & Sons, Inc.

This reprint is for sale in the People's Republic of China only and exclude Hong Kong and Macau.

English reprint Copyright © 2003 by John Wiley & Sons, Inc. and Publishing House of Electronics Industry.

本书英文影印版由 John Wiley & Sons 授予电子工业出版社。未经出版者预先书面许可,不得以任何形式或手段复制或抄袭本书内容。

此版本仅限在中华人民共和国境内(不包括香港、澳门特别行政区以及台湾地区)发行与销售。

版权贸易合同登记号:图字:01-2003-6995

图书在版编目(CIP)数据

智能系统:结构、设计与控制 = Intelligent Systems: Architecture, Design, and Control/ (美)梅斯特(Meystel, A. M.)等著. - 北京:电子工业出版社, 2003.11

(国外计算机科学教材系列)

ISBN 7-5053-9231-X

I. 智... II. 梅... III. 人工智能-研究-英文 IV. TP18

中国版本图书馆CIP数据核字(2003)第091930号

责任编辑:赵红燕

印刷者:北京兴华印刷厂

出版发行:电子工业出版社 <http://www.phei.com.cn>

北京市海淀区万寿路173信箱 邮编:100036

经 销:各地新华书店

开 本:787 × 980 1/16 印张:44.75 字数:1002千字

版 次:2003年11月第1版 2003年11月第1次印刷

定 价:69.00元

凡购买电子工业出版社的图书,如有缺损问题,请向购买书店调换;若书店售缺,请与本社发行部联系。

联系电话:(010)68279077。质量投诉请发邮件至 zltz@phei.com.cn, 盗版侵权举报请发邮件至 dbqq@phei.com.cn。

出版说明

21 世纪初的 5 至 10 年是我国国民经济和社会发展的关键时期,也是信息产业快速发展的关键时期。在我国加入 WTO 后的今天,培养一支适应国际化竞争的一流 IT 人才队伍是我国高等教育的重要任务之一。信息科学和技术方面人才的优劣与多寡,是我国面对国际竞争时成败的关键因素。

当前,正值我国高等教育特别是信息科学领域的教育调整、变革的重大时期,为使我国教育体制与国际化接轨,有条件的高等院校正在为某些信息学科和技术课程使用国外优秀教材和优秀原版教材,以使我国在计算机教学上尽快赶上国际先进水平。

电子工业出版社秉承多年来引进国外优秀图书的经验,翻译出版了“国外计算机科学教材系列”丛书,这套教材覆盖学科范围广、领域宽、层次多,既有本科专业课程教材,也有研究生课程教材,以适应不同院系、不同专业、不同层次的师生对教材的需求,广大师生可自由选择和自由组合使用。这些教材涉及的学科方向包括网络与通信、操作系统、计算机组织与结构、算法与数据结构、数据库与信息处理、编程语言、图形图像与多媒体、软件工程等。同时,我们也适当引进了一些优秀英文原版教材,本着翻译版本和英文原版并重的原则,对重点图书既提供英文原版又提供相应的翻译版本。

在图书选题上,我们大都选择国外著名出版公司出版的高校教材,如 Pearson Education 培生教育出版集团、麦格劳-希尔教育出版集团、麻省理工学院出版社、剑桥大学出版社等。撰写教材的许多作者都是蜚声世界的教授、学者,如道格拉斯·科默(Douglas E. Comer)、威廉·斯托林斯(William Stallings)、哈维·戴特尔(Harvey M. Deitel)、尤利斯·布莱克(Uyless Black)等。

为确保教材的选题质量和翻译质量,我们约请了清华大学、北京大学、北京航空航天大学、复旦大学、上海交通大学、南京大学、浙江大学、哈尔滨工业大学、华中科技大学、西安交通大学、国防科学技术大学、解放军理工大学等著名高校的教授和骨干教师参与了本系列教材的选题、翻译和审校工作。他们中既有讲授同类教材的骨干教师、博士,也有积累了几十年教学经验的老教授和博士生导师。

在该系列教材的选题、翻译和编辑加工过程中,为提高教材质量,我们做了大量细致的工作,包括对所选教材进行全面论证;选择编辑时力求达到专业对口;对排版、印制质量进行严格把关。对于英文教材中出现的错误,我们通过作者联络和网上下载勘误表等方式,逐一进行了修订。

此外,我们还将与国外著名出版公司合作,提供一些教材的教学支持资料,希望能为授课老师提供帮助。今后,我们将继续加强与各高校教师的密切联系,为广大师生引进更多的国外优秀教材和参考书,为我国计算机科学教学体系与国际教学体系的接轨做出努力。

电子工业出版社

教材出版委员会

- | | | |
|-----|-----|---|
| 主 任 | 杨芙清 | 北京大学教授 中国科学院院士 北京大学信息与工程学部主任 北京大学软件工程研究所所长 |
| 委 员 | 王 珊 | 中国人民大学信息学院院长、教授 |
| | 胡道元 | 清华大学计算机科学与技术系教授 国际信息处理联合会通信系统中国代表 |
| | 钟玉琢 | 清华大学计算机科学与技术系教授 中国计算机学会多媒体专业委员会主任 |
| | 谢希仁 | 中国人民解放军理工大学教授 全军网络技术研究中心主任、博士生导师 |
| | 尤晋元 | 上海交通大学计算机科学与工程系教授 上海分布计算技术中心主任 |
| | 施伯乐 | 上海国际数据库研究中心主任、复旦大学教授 中国计算机学会常务理事、上海市计算机学会理事长 |
| | 邹 鹏 | 国防科学技术大学计算机学院教授、博士生导师 教育部计算机基础课程教学指导委员会副主任委员 |
| | 张昆藏 | 青岛大学信息工程学院教授 |

PREFACE

INTELLIGENCE AS A TOOL OF EVOLUTION

About 600 million years ago, there was an unusual explosion in the biosphere of the earth. Biologists call it the *Cambrian explosion*. The amount and diversity of living creatures that emerged during the Cambrian explosion far exceeded anything that happened before or after this unusual period in the ecological history of the earth. A comparison with the middle part of the sigmoidal¹ curve is a suggestive metaphor for the Cambrian explosion although it leaves more to our imagination rather than offering any explanation of what happened.

The famous scientist S. Gould made an interesting observation:

The world of life was quiet before and it has been relatively quiet ever since. The recent evolution of consciousness must be viewed as the most cataclysmic happening since the Cambrian if only for its geological and ecological effects. Major events in evolution do not require the origin of new designs. The flexible eucaryotes² will continue to produce novelty and diversity so long as one of its latest products controls itself well enough to assure the world a future.³

Undoubtedly, the latest products of evolution are we, the people. We are the products who must control ourselves well. This is why the evolution of consciousness happened; it is supposed to *assure the world a future*. S. Gould made an interesting observation: We might not see new evolutionary designs. Apparently, the richness, flexibility, and inventiveness of our brain would compensate for the absence of new evolutionary designs. The brains of living creatures, even in their rudimentary form, guide them toward development of new designs for the evolution (our thoughts, plans, inventions, visual arts, music, and poetry).

Evolution and intelligence are the major known tools in producing a beneficial response to anything that may happen to a living creature. They help the creature survive in most situations, expected and unexpected. Here we should proceed with caution: The concept of the *expected event* presumes a creature that can have expectations. Evolution

¹*Sigmoidal curve* describes processes that initially grow slowly, then gradually accelerate, achieving a rapid rate of growth, and then slow down, gradually achieving the end with a very low rate of growth.

²Eucaryotes are multichromosome living cells, as opposed to procaryotes that are single-chromosome cells.

³Stephen Jay Gould, *Ever Since Darwin: Reflections in Natural History*, Norton & Company, New York, 1977, p. 118.

works to the benefit or the successful outcome for a *species*; the idea of expectation in this case is at least puzzling. The idea of the *benefit* or the *success* is puzzling as well. Yes, the need for survival is well known. But what is the source of this need? Even more difficult is the idea of *success*. The latter presumes a *goal*. It is customary to link the goal with intelligence, but what might be the goal of the evolution?

Well, *evolution* and *intelligence* have something very important in common. Both affect our lives the most, and yet both are understood the least.

WE ARE THE TOOLS OF OUR INTELLIGENCE

Certainly, the productivity of design,⁴ provided by the old chromosome-based mechanism, has its limitations. It achieved its peak at the time of the Cambrian period, and now, as our brain takes over, a new explosion is on the way. The intricacy of our brain navigates unexpectedly the subtle processes of decision making, beyond this organ's presently known capabilities, with its slow wetware-based neurons placed into an unreliable body prone to hedonism and addictions. In a hectic outburst of events compressed into one century, the brains of mankind have created a surprising engineering phenomenon: *intelligent systems*, which can work for their evolution much more efficiently than we, the people, can.

This thought is intuitively acceptable for those of us who continue researching the surrounding reality even after graduation. Computer-aided design and data mining are not buzzwords anymore; there are innovations actually produced by machines. The decision-making role of all-pervasive automated machines and various software packages is a fact of our lives. This is what happens—automation is coming to the domain of decision making rapidly and maybe even faster than it conquers the area of menial works. (This might be an alarming sign, but it is probably linked with the surprising fact that the market still creates more opportunities for menial jobs than for decision making.)

Evolution, until now the unchallenged domain of living organisms, may soon become possible for robots as well. A computer-based form of evolution—nature's own design strategy—has succeeded in designing LEGO structures without any assistance from humans, by the virtue of learning (Brandeis University). A human-like robot follows passersby with its eyes; a robot-drummer entertains the public (MIT). A robot-vehicle recognizes the edge of the road (Carnegie Mellon). A dune-buggy, controlled by the planner-navigator-pilot hierarchy, travels via cluttered environment by trial-and-error to the goal, then returns much faster because it had already seen the environment, remembered it, and planned a better motion trajectory (Drexel University). Autonomous vehicles can move with no human help at a speed of 55 mph on a highway (Universität der Bundeswehr, München, Germany). A squad of autonomous vehicles travels cooperatively at a speed of 20 mph in a cross-country environment (National Institute of Standards and Technology). Robotic brains can control manipulators, allowing them to carry heavy things cooperatively, not to speak about playing ping-pong which was already achieved years ago. These are mankind's first successful leaps from the early concepts of decision making based on expert systems into the futuristic realm of multiresolutional thinking.

⁴Naturally, we talk about design of a living creature. Evolution is interpreted frequently as a mechanism for designing the living creature. Probably, *self-design* is meant.

THE MOLECULE OF INTELLECT OR EVEN LIFE

It is not so difficult to discover that both evolution and intelligence use the same set of techniques: Both transform real experiences into symbolic representation and keep the messages in a well-organized, computationally efficient form; use these messages for searching groups of similarity and generalizing them; repeat this generalization recursively so that the nested hierarchies of efficiently organized information are being developed; increase their efficiency by focusing attention upon limited subsets of information; and use searching processes to combine elements of this information into messages that could not be obtained from the experiences.

Compact packages of operators, comprising of "grouping-focusing attention-combinatorial search" triplets in various combination, consume the arriving information and transform it into multiresolutional architectures. A simple feedback loop well known from the views of cybernetics could not be decisive in explaining the phenomena of the mind. In this book, we demonstrate that metaphorically speaking, the decision-making processes are realized via distributing the feedback loop over the multiresolutional architecture of information. Or even more accurately, via imposing the multiresolutional architecture upon the feedback mechanism. This is how the mind was built through the history of its development. This is how the model of mind is visualized by the authors of this book.

MULTIRESOLUTIONAL MIND

The concept of multiresolutional (multiscale, multigranular) information representation is the most formidable insight of the mankind in a rush to design new tools for a further leap in the process of evolution. People always distinguish between actual view and the bird's-eye view; smaller picture and larger picture; and the faraway look and close-up. This is the century when we have eventually discovered that our mind uses views of different granularity and scale for the benefits of decision making. This book demonstrates how people employ multiresolutional representations and make decisions of different resolutions.

This concept came simultaneously from different communities and appeared in different disguises. Researchers in computer vision discovered pyramidal image representation. Fractal people recognized this multiscale key to information representation as a mechanism of the construction of nature. European scientists made multigranular representation a part of their new science "synergetics." Practical engineers employed it within "finite element method." Mathematicians have not yet succeeded in unlocking the mystery hidden in *nonstandard analysis*.⁵ However, they successfully use many levels of resolution as a practical method of solving partial differential equations ("multigrid methods").

The multiscale habits of thinking reveal something about the architecture of the human mind. Authors are convinced that the key issues of the "mind-design" can be resolved only by restoring the mind's structure in a multiresolutional fashion. Although we cannot observe or touch the structure of our mind, we have to restore it from watching the records of its multiscale functioning. This process of top-down/bottom-up

⁵Nonstandard analysis, a domain of logic discovered by A. Robinson, contemplates the possibility of a noncontradictory bridge between the continuous and discrete mathematics.

restoration of things that cannot be available to our immediate observation is similar to *reverse engineering*. (This term can be found in the 1993 documents⁶; in the context of cognitive science, it was used by D. Dennett⁷.)

The results of mind restoration in the form of multiresolutional models described in this book allow for constructive understanding and simulation of our cognitive processes. In addition, multiresolutional models can be used for constructing and exploring machines and organizations that we call *intelligent systems*. Intelligent systems mimic human abilities to perceive the world, to collect and organize knowledge, to imagine things and make plans about them, to execute these plans and control ourselves. Remember that if we are able to control ourselves well enough, we may *assure the world a future*.

So far, we have been successful in inventing what has already been invented by nature. Computer scientists, with biologists, have succeeded in simulating the processes of the evolution of eye as an organ, and with engineers, have analyzed the process of evolving robotic skills of building bridges. In hindsight, the algorithm for discovery of sophisticated engineering devices turned out to be very simple. In reality, it took many centuries for humans to capture the skills of engineering design, develop rational plans of actions that take planners weeks to design, and compute trajectories of motion that require engineers hours to design.

ABOUT THIS BOOK

This book is about robotic brains as they should be designed and implemented in the very near future. The biologists and psychologists will find the engineering views on cognitive processes in human brain. Also, they can find numerous suggestions from two engineers on how they should understand human brains. Engineers should consider these suggestions as engineering metaphors. However, in the engineering part, the book contains the outcomes of many years of experience in engineering design and industrial implementation. Several doctoral and masteral theses were developed under the guidance of the authors; the essence of these researches was included in the book. The authors have merged together the results of their research obtained for the last 15 years. Some of these results happen to coincide, and they were very persuasive for the authors. Part of its materials precipitated from working together since 1994.

Our engineering recommendations are verified by implementing them in a realistic environment. Indeed, multiresolutional representation reduces the complexity of computation. Planning can be applied as a nested search process at all levels of resolution. Elementary loop of functioning must be specified for all levels of resolution before we start other engineering activities; a lot of time and money will be saved. Multiple levels of resolution can work jointly and coherently.

This book is intended to serve as a textbook for graduate courses in various disciplines: engineering (including robotics, mechatronics, and automatic control), business management, computer and information science. However, we would expect that cognitive scientists, psychologists, and biologists will benefit in using this as a text, too. Quiz and test problems are included at the end of each chapter.

⁶See a legal document in URL <http://www.lgu.com/cr46.htm>

⁷D. Dennett, Cognitive science as reverse engineering, in *Brainchildren, Essays on Designing Minds*, MIT Press and Penguin, 1998.

The book is illustrated by the results of application of the new theory for equipping numerous intelligent machines, including industrial robots and autonomous vehicles. We did not address several important issues related to intelligence, like natural language understanding. However, our methodology is expected to be instrumental in this case, too.

In the last 15 years or so, we have worked on these issues in close cooperation. We have achieved the highest level of mutual understanding, and it would be very difficult to determine who wrote what in this book. Nevertheless, even this level of cooperation would be insufficient for preparing the manuscript without help and contribution from our colleagues (in alphabetical order): U. Bar-Am, R. Bhatt, S. Bhasin, R. Bostelman, D. Coombs, N. Dagalakakis, S. Drakunov, P. Filipovich, D. Gaw, G. Grevera, T. Hong, J. Horst, H.-M. Huang, A. Jacoff, E. Koch, A. Lacaze, S. Legowik, E. Messina, M. A. Meystel, J. Michaloski, Y. Moscovitz, K. Murphy, M. Nashman, R. Nawathe, L. Perlovsky, F. Proctor, I. Rybak, W. Rippey, H. Scott, S. Szabo, C. Tasoluk, and S. Uzzaman. We thank all of them for their constant and continuous support in the past 10 to 15 years.

ALEX MEYSTEEL
JIM ALBUS

August 2001

目录概览

| | |
|---|-----|
| 第1章 在普通和结构化系统中的智能 | 1 |
| Intelligence in Natural and Constructed Systems | |
| 第2章 理论基础 | 38 |
| Theoretical Fundamentals | |
| 第3章 知识表示 | 100 |
| Knowledge Representation | |
| 第4章 引用体系结构 | 158 |
| Reference Architecture | |
| 第5章 动机、目标和值的判定 | 188 |
| Motivations, Goals, and Value Judgment | |
| 第6章 感觉处理 | 220 |
| Sensory Processing | |
| 第7章 行为生成 | 257 |
| Behavior Generation | |
| 第8章 多种解决方案规化：理论框架 | 343 |
| Multiresolutional Planning: A Sketch of the Theory | |
| 第9章 规化者/执行者模块的多种层次 | 399 |
| Multiresolutional Hierarchy of Planner/Executor Modules | |
| 第10章 学习 | 457 |
| Learning | |
| 第11章 智能系统的多种解决方案的应用程序 | 560 |
| Applications of Multiresolutional Architectures for Intelligent Systems | |
| 第12章 智能系统：科学和工程中新的范型的先驱 | 642 |
| Intelligent Systems: Precursor of the New Paradigm in Science and Engineering | |

CONTENTS

1 INTELLIGENCE IN NATURAL AND CONSTRUCTED SYSTEMS 1

- 1.1 Introduction, 1
- 1.2 Brief Overview of the Evolving Concepts of Mind and Intelligence, 4
- 1.3 Intelligent Systems: Can We Distinguish Them from Nonintelligent Systems?, 12
- 1.4 Intelligence: Product and Tool of Behavior and Communication, 16
 - 1.4.1 Advantageous Behavior, 16
 - 1.4.2 Efficient Symbolic Representation, 17
 - 1.4.3 Elementary Loop of Functioning, 19
- 1.5 Evolution of Automatisms, 20
 - 1.5.1 Learning Automaton, 20
 - 1.5.2 Concept of Automatism and How It Can Be Learned, 20
 - 1.5.3 From Reflexes and Rules to Programs, 22
 - 1.5.4 From Programs to Self-Organization, 23
- 1.6 From Agent to Multiscale Communities of Agents, 24
 - 1.6.1 The Concept of “Agents” and Its Place in the State of the Art, 24
- 1.7 Cognitive Agents and Architectures, 29
- References, 32
- Problems, 36

2 THEORETICAL FUNDAMENTALS 38

- 2.1 Mathematical Framework of the Architectures for Intelligent Systems, 38
 - 2.1.1 Role of Discrete Mathematics in the Development of the Formal Theory of Intelligent Systems, 38
 - 2.1.2 What Are the *Objects* to Which *Discrete Mathematics* Is Applied?, 40
 - 2.1.3 What *Jobs* Does Discrete Mathematics Do? What Are Our *Objectives*?, 41
- 2.2 Formal Model of Intelligent Systems and Processes, 42
 - 2.2.1 Fundamental Procedures of Multiresolutional Calculus, 44

| | | |
|-------|---|----|
| 2.2.2 | Existing Definitions of a Set, | 46 |
| 2.2.3 | What Is a <i>State</i> ? How Is It Related to the Concept of <i>Object</i> ? What Is <i>Change</i> ?, | 50 |
| 2.2.4 | Formation of New Objects via the GFS Triplet, | 51 |
| 2.2.5 | Relations among the Objects: What Is a <i>Relation</i> ? What Are the Properties of Relations? Can We Measure Relations?, | 54 |
| 2.2.6 | Representation and Reality, | 54 |
| 2.2.7 | Models in the Form of Automata: Primitive Agents, | 56 |
| 2.2.8 | Multiresolutional Automata, | 58 |
| 2.2.9 | Autonomy and Goal-Orientedness of Intelligent Systems, | 60 |
| 2.3 | Necessary Terminology and Assumptions, | 60 |
| 2.3.1 | Coordinates, Scope, and Resolution, | 60 |
| 2.3.2 | States and State-Space, | 62 |
| 2.3.3 | From Objects toward Entities, | 64 |
| 2.3.4 | Clusters and Classes, | 64 |
| 2.3.5 | Distinguishability, | 65 |
| 2.3.6 | Representation, | 66 |
| 2.4 | Construction and Properties of Objects, | 67 |
| 2.4.1 | Formation of New Categories, | 67 |
| 2.4.2 | Recursive Hierarchies and Heterarchies of Representation, | 68 |
| 2.5 | Extracting Entities from Reality, | 70 |
| 2.5.1 | Natural Grouping of Components, | 70 |
| 2.5.2 | Grouping within Scientific Processes, | 73 |
| 2.5.3 | Grouping Leads to the Multiresolutional Architecture, | 76 |
| 2.5.4 | Differences between Abstraction, Aggregation, and Generalization, | 79 |
| 2.6 | Grouping + Filtering + Search: The Elementary Unit of Self-Organization, | 80 |
| 2.6.1 | Concept of GFS, | 80 |
| 2.6.2 | Functioning of GFS, | 81 |
| 2.7 | Relative Intelligence and Its Evolution, | 83 |
| 2.8 | On the Resemblances among Processes of Structuring in Nature and Representation, | 87 |
| 2.8.1 | Issue of Resemblance, | 87 |
| 2.8.2 | On the Resemblance among the Algorithms Applied for Structuring, | 88 |
| 2.9 | Semiotic Framework of the Architectures for Intelligent Systems, | 89 |
| 2.9.1 | What Is Semiotics?, | 89 |
| 2.9.2 | Semiotic Closure, | 90 |
| 2.9.3 | Semiosis: The Process of Learning in Semiotic Systems, | 92 |
| 2.9.4 | Reflection and Consciousness, | 94 |
| | References, | 96 |
| | Problems, | 97 |

| | | |
|-------|--|-----|
| 3.1 | Problem of Representing the Natural World, | 100 |
| 3.1.1 | Unbearable Richness of the Reality, | 100 |
| 3.1.2 | Epistemology, | 102 |
| 3.1.3 | Evolution of the Theories of Knowledge, | 103 |
| 3.1.4 | Semiotics and Future Perspectives, | 106 |

- 3.2 What Is Knowledge?, 108
 - 3.2.1 Knowledge as a Phenomenon, 108
 - 3.2.2 Knowledge-Related Terminology, 109
 - 3.2.3 Storing the Knowledge, 112
 - 3.2.4 Why Does the Need for Representing Knowledge Emerge?, 113
- 3.3 Knowledge Representation in the Brain: Acquiring Automatisms, 115
 - 3.3.1 An Elementary Information Processing Unit: A Neuron, 115
 - 3.3.2 A System for Searching and Storing Patterns: A Neural Net, 116
- 3.4 Sensory and Symbolic Representations in the Brain, 117
 - 3.4.1 General Comments, 117
 - 3.4.2 Sensory Images, 117
 - 3.4.3 Symbolic Representations in the Brain, 119
- 3.5 Reference Frame, Imagination, and Insight, 120
- 3.6 Principles of Knowledge Representation, Entities, and Relational Structures, 121
 - 3.6.1 Nested Hierarchical Knowledge Organization, 122
 - 3.6.2 Definitions and Premises of the Principles of Knowledge Representation, 124
 - 3.6.3 Definitions of Knowledge-Related Mechanisms of ELF Functioning, 133
 - 3.6.4 Types and Classes of Entities, 136
 - 3.6.5 General Characterization of the D-Structure, 140
 - 3.6.6 Properties of Labels, 143
- 3.7 Multiresolutional Character of Knowledge and Its Complexity, 147
 - 3.7.1 State-Space Decomposition, 147
 - 3.7.2 Accuracy, 148
 - 3.7.3 Nestedness of Knowledge, 149
 - 3.7.4 Recursive Algorithm of Constructing Multiscale Knowledge Representations, 150
- 3.8 Virtual Phenomena of Knowledge Representation, 151
 - 3.8.1 Representation for Immediate Sensory Processing, 151
 - 3.8.2 Intermediate Representation, 152
 - 3.8.3 Long-Term Memory Representation, 153
- References, 153
- Problems, 156

4

REFERENCE ARCHITECTURE

158

- 4.1 Components of a Reference Architecture, 158
 - 4.1.1 Actuators, 158
 - 4.1.2 Sensors, 159
 - 4.1.3 Sensory Processing, 159
 - 4.1.4 World Model, 159
 - 4.1.5 Value Judgment, 159
 - 4.1.6 Behavior Generation, 160
- 4.2 Evolution of the Reference Architecture for Intelligent Systems, 160
- 4.3 Hierarchy with Horizontal "In Level" Connections, 163
- 4.4 Levels of Resolution, 165
- 4.5 Neural Components of the Architecture, 169

- 4.6 Behavior-Generating Hierarchy, 171
- 4.7 Analysis of Multiresolutional Architectures, 172
 - 4.7.1 Elementary Loop of Functioning (ELF), 172
 - 4.7.2 Primary Decomposition of an ELF, 175
 - 4.7.3 Hierarchies of ELFs: the Essence of NIST-RCS, 177
 - 4.7.4 Integrated NIST-RCS Modules, 178
- 4.8 Agent-Based Reference Architectures, 180
 - 4.8.1 Elements of Intelligent Software, 180
 - 4.8.2 Functioning of the Agent-Based Level, 181
- References, 184
- Problems, 186

5

MOTIVATIONS, GOALS, AND VALUE JUDGMENT

188

- 5.1 Internal Needs versus External Goals, 188
 - 5.1.1 Neurophysiological Models, 188
 - 5.1.2 From Instinct to Motivation to Drive and to Emotion, 191
 - 5.1.3 Motivation, 192
 - 5.1.4 From Motives to Goals, 193
 - 5.1.5 Various Approaches, 194
 - 5.1.6 Development of the Concept of "Goal", 196
 - 5.1.7 Cognitive Theories of Goal Formation and Comparison, 197
- 5.2 Value Judgments, 199
 - 5.2.1 General Definitions, 199
 - 5.2.2 Limbic System, 200
 - 5.2.3 Value State-Variables, 201
 - 5.2.4 VJ Modules, 204
 - 5.2.5 Value State-Variable Map Overlays, 207
- 5.3 Achieving the Goal: Optimization via the Calculus of Variations, 207
 - 5.3.1 Notation and Basic Premises, 207
 - 5.3.2 A Linearized Third-Order Plant: Model of a DC Motor, 208
 - 5.3.3 Optimization via the Calculus of Variations, 209
 - 5.3.4 Results and Discussion, 216
- References, 218
- Problems, 219

6

SENSORY PROCESSING

220

- 6.1 In-level and Inter-level Processes, 220
 - 6.1.1 Focusing of Attention (F of GFS), 221
 - 6.1.2 Creation of Grouping Hypotheses (G and S of GFS), 223
 - 6.1.3 Computation Attributes for Grouping Hypotheses (G of GFS), 224
 - 6.1.4 Selection and Confirmation (S of GFS), 225
 - 6.1.5 Classification, Recognition, and Organization of Entities, 226
- 6.2 Sensory Processing as a Module of the Level, 228
 - 6.2.1 Information Sources, 230
 - 6.2.2 State-Space Tessellation: Sampling, 231
 - 6.2.3 Noise, Uncertainty, and Ambiguity, 232
 - 6.2.4 Creation of Hypotheses and Testing, 233
 - 6.2.5 Initialization, 236

- 6.3 Hierarchy of Sensory Processing, 238
 - 6.3.1 Naturally Emerging Hierarchies of Representation in SP, 238
 - 6.3.2 Processing at the Two Adjacent Levels of the Highest Resolution, 240
 - 6.3.3 What Happens at the Levels Above?, 247
- 6.4 Multiresolutional Nature of Sensory Processing, 251
- References, 253
- Problems, 255

7

BEHAVIOR GENERATION

257

- 7.1 Preliminary Concepts of Multiresolutional Behavior Generation, 257
 - 7.1.1 Definitions, 257
 - 7.1.2 Behavior Generation as a Recursive Synthesis of Instantiations from Generalizations, 263
- 7.2 BG Architecture, 265
 - 7.2.1 Virtual Loops, 265
 - 7.2.2 Real-Time Control and Planning: How They Are Affected by the Sources of Uncertainty, 270
 - 7.2.3 Nesting of the Virtual ELF's, 271
- 7.3 Strategy of Multiresolutional Control: Generation of a Nested Hierarchy, 273
 - 7.3.1 Off-line Decision-Making Procedures of Planning-Control, 273
 - 7.3.2 Nested Hierarchical Information Refinement during On-line Decision Making, 275
 - 7.3.3 Nested Modules, 280
- 7.4 Overall Organization of Behavior Generation, 285
 - 7.4.1 Main Concept of Computing Behavior, 285
 - 7.4.2 BG Modules, 288
 - 7.4.3 Realistic Examples of Behavior Generation, 291
 - 7.4.4 Generalization upon Realistic Examples: A Sketch of the Theory, 296
 - 7.4.5 Algorithm of Multiresolutional Hierarchical Planning (NIST-RCS Planner), 297
 - 7.4.6 BG Module: An Overview, 302
- 7.5 PLANNER, 309
 - 7.5.1 Computation Process of Planning, 309
 - 7.5.2 Epistemology and Functions of the PLANNER, 310
 - 7.5.3 Planning in Multiresolutional Space versus Planning in Abstraction Spaces, 312
 - 7.5.4 Planning in the Task Space versus Motion Planning, 315
 - 7.5.5 Reactive versus Deliberative Decision Making, 316
 - 7.5.6 What Is Inside the PLANNER?, 317
- 7.6 EXECUTOR: Its Structure and Functioning, 330
 - 7.6.1 Processing the Results of Planning, 330
 - 7.6.2 Structure of EXECUTOR, 332
 - 7.6.3 Operations of the EXECUTOR, 334
 - 7.6.4 EXECUTOR as a TASK GENERATOR, 336
- 7.7 Conclusions: Integrating BG in the Intelligent System, 337
- References, 338
- Problems, 341

- 8.1 Introduction to Planning, 343
 - 8.1.1 Overview of the Key Results in the Area of Planning, 343
 - 8.1.2 Definitions Related to Planning, 345
 - 8.1.3 Planning as a Stage of Control, 347
- 8.2 Emerging Problems in Planning, 349
 - 8.2.1 Generic Problems of Behavior Generation, 349
 - 8.2.2 Structural Sources of Problems, 350
 - 8.2.3 Representation and Planning, 350
 - 8.2.4 Classification of Planning Problems in Intelligent Systems, 352
- 8.3 Planning of Actions and Planning of States, 354
 - 8.3.1 Algorithms of Planning, 354
 - 8.3.2 Visibility-Based Planning, 354
 - 8.3.3 Local Planning: Potential Field for World Representation, 356
 - 8.3.4 Global Planning: Search for the Trajectories, 356
- 8.4 Linkage between Planning and Learning, 357
 - 8.4.1 Learning as a Source of Representation, 357
 - 8.4.2 Interrelations between Planning and Learning, 358
- 8.5 Planning in Architectures of Behavior Generation, 358
 - 8.5.1 Hierarchical Multiresolutional Organization of Planning, 358
 - 8.5.2 Case Study: A Pilot for an Autonomous Vehicle, 360
- 8.6 Path Planning in a Multidimensional Space, 366
 - 8.6.1 State-Space Representation, 366
 - 8.6.2 Expert Rules/Heuristics, 368
 - 8.6.3 Techniques to Reduce Computation Time, 370
 - 8.6.4 Experimental Results, 371
- 8.7 Multiresolutional Planning as a Tool of Increasing Efficiency of Behavior Generation, 373
 - 8.7.1 Multiresolutional Planning Embodies the Intelligence of a System, 373
 - 8.7.2 Multiresolutional Planning Reduces the Complexity of Computations, 374
 - 8.7.3 Applying the General S^3 -Search Algorithm for Planning with Complexity Reduction, 379
 - 8.7.4 Tessellation, 381
 - 8.7.5 Testing of the Representation, 384
 - 8.7.6 Search, 387
 - 8.7.7 Consecutive Refinement, 390
 - 8.7.8 Evaluation of Complexity, 393
- References, 395
- Problems, 398

- 9.1 Hybrid Control Hierarchy, 399
- 9.2 Theoretical Premises, 401
- 9.3 Canonical Hybrid PLANNER/EXECUTOR Module, 404