Part I

Introduction

1 History and potential of neuromorphic robotics

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Neuromorphic and brain-based robots are not encapsulated in a single field with its own journal or conference. Rather, the field crosses many disciplines, and groundbreaking neuromorphic robot research is carried out in computer science, engineering, neuroscience, and many other departments. The field is known by many names: biologically inspired robots, brain-based devices, cognitive robots, neuromorphic engineering, neurobots, neurorobots, and many more. Arguably, the field may have begun with William Grey Walter's turtles, created in the 1950s, whose simple yet interesting behaviors were guided by an analog electronic nervous system. Another landmark was the fascinating thought experiments in the book by Valentino Braitenberg, *Vehicles: Experiments in Synthetic Psychology*. Braitenberg's *Vehicles* inspired a generation of hobbyists and scientists, present company included, to use synthetic methodology (Braitenberg's term) to study brain, body, and behavior together. We like to think of synthetic methodology as "understanding through building" and it is certainly an apt mission statement for neuromorphic and brain-based robots.

It has been almost 90 years since the popular word "robot" first appeared in Karel Capek's play *R.U.R.* With the dawn of the twenty-first century, our expectations are high for a new scientific paradigm and a major technological advancement in the field of robotics. In this time robots have become prevalent in our society. Robots can be found in commercial, manufacturing, military, and entertainment applications. We now have robotic vacuum cleaners, robotic soccer players, and autonomous vehicles on the ground, in the sky, and beneath the ocean. Because of major technical and empirical advances in the brain sciences over the last few decades, the time appears right for integrating the exciting fields of robotics and neuroscience. This promising area of research and the subject of this book, which we term neuromorphic and brain-based robotics, may generate the paradigm shift for truly intelligent machines.

Robots are increasing our productivity and quality of life in industry, defense, security, entertainment, and household chores. However, the behavior of these robots pales compared with that of animals and insects with nervous systems. Biological organisms survive in dynamic environments and display flexibility, adaptability, and survival capabilities that far exceed any artificial systems. Neuromorphic and brain-based robotics are exciting and emerging research fields that investigate the roots of biological

Neuromorphic and Brain-Based Robots, eds. Jeffrey L. Krichmar and Hiroaki Wagatsuma. Published by Cambridge University Press.

intelligence by embodying models of the brain on robotic platforms. Moreover, because neuromorphic and brain-based robotics follows a working model (i.e. the biological brain and body), we believe this field will lead to autonomous machines that we can truly call intelligent.

Neuromorphic and brain-based robots are physical devices whose control system has been modeled after some aspect of brain processing. Because the nervous system is so closely coupled with the body and situated in the environment, brain-based robots can be a powerful tool for studying neural function. Brain-based robots can be tested and probed in ways that are not yet achievable in human and animal experiments. The field of neuromorphic and brain-based robots is built on the notion that the brain is embodied in the body and the body is embedded in the environment.

In the real biological nervous system, this embodiment mediates all the sensations and governs motion, and is also crucial for higher order cognition, and notions of mind and self. The question of how our mind is constructed from physical substrates such as the brain and body are still a mystery. A synthetic approach occupies an important position in investigating how complex systems, such as the brain, give rise to intelligent behavior through interactions with the world. The concept is highlighted by "embodiment" in the fields of robotics, artificial intelligence, and cognitive science. It argues that the mind is largely influenced by the state of the body and its interaction with the world.

The neuromorphic and brain-based robotic approaches can provide valuable heuristics for understanding how the brain works both empirically and intuitively. Neurologists analytically investigate whether the brain is healthy or impaired due to neurological disorders. Neuroscientists probe different areas of the brain to determine which brain regions are necessary for a specific function. By using a synthetic methodology, neurobiologically inspired robots can constructively exhibit how the brain works through its interaction with the body, the environment, and other agents in real world situations. We believe that neuromorphic and brain-based robotics will provide the groundwork for the development of intelligent machines, contribute to our understanding of the brain and mind, as well as how the nervous system gives rise to complex behavior.

Neuromorphic and brain-based robotics is an exciting field of research that has a growing community of researchers with a wide range of multidisciplinary talents and backgrounds. We wrote this book as an introduction to the recent advances in neuromorphic and brain-based robotics. The contributing authors speculate how robots can be used to better understand brain science and what properties of the nervous system are necessary to produce truly intelligent robots.

We divided the chapters of this book into logical sections starting with physical robotic platforms, progressing to case studies using brain-based robots, to several articles on philosophical considerations with future brain-based robots, and finally important ethical issues as robots become so intelligent that we have to think about the mental state of the robots.

In Part II on neuromorphic robots, we directly consider how the body of a robot affects thinking and cognition. Hosoda from Osaka University describes an anthropomorphic hand, which he designed to be much more natural in its movement and sensing than a conventional robotic hand. Different types of objects can be recognized through the hand's movement and posture. This study is a direct demonstration of how the body shapes the way we think. Mitchinson and colleagues from Sheffield University have been studying the whisker system, which is the rat's primary means of sensing its environment. They used high-speed video of real rat whisker movements to guide the development of a complete robotic whisker system. The robot uses its artificial whisker system to switch between several behaviors. The mechanical and electrical design of the Osaka and Sheffield groups is extremely impressive. Many lessons remain to be learned through the construction of ingenious biomimetic devices. However, it is also important to make neuromorphic and brain-based robots available to a wider audience. Most computational neuroscientists are not mechanical engineers and do not have ready access to electronics and machine shops. Felch and Granger, who are computational neuroscientists with expertise in robot design, have developed the Brainbot to meet this need. The Brainbot has a visual system, reaching system, language system, and software packages to make neurobotics readily accessible to researchers who are not necessarily "gear heads."

In Part III on architectures and approaches, several authors present case studies on the embodied approach to neuroscientific study. Rats have exquisite navigational abilities that allow them to form cognitive maps of their environment. Wyeth and colleagues from the University of Queensland in Australia have used recent findings on place cells in the hippocampus and grid cells in the entorhinal cortex to develop a neurally inspired navigation system they call RatSLAM. They show impressive mapping results with RatSLAM on the streets of Brisbane, as well as navigation and communication of places between two robots with RatSLAM. Uchibe and Doya at the Okinawa Institute of Science and Technology have developed the CyberRodent project in which they use multiple robots to explore learning algorithms, neuromodulation, and robot interactions. In their chapter, they use the CyberRodent paradigm along with evolutionary algorithms to develop brain circuits that use both extrinsic and intrinsic rewards to develop autonomous behaviors. Wilkes and colleagues from Vanderbilt University review their work with the humanoid robot ISAC (Intelligent Soft Arm Control) as a means of developing a cognitive architecture. They present working memory and mental rehearsal experiments using this paradigm. Weng at Michigan State University has pioneered the field of autonomous mental development for cognitive robots. In their chapter, Ji, Weng, and Prokhorov present a model of the visual "what" and "where" pathways that could be used in neuromorphic systems for recognizing general objects from complex backgrounds, allowing a location- or type-command from a motor end to dynamically modify a network's internal neuromorphic operations. Barakova and Feijs, from Eindhoven University of Technology in the Netherlands, use various robotic paradigms to study autism spectrum disorder (ASD). Because children with ASD have difficulties with social interaction, Barakova and Feijs have used their robots as a form of therapy for these children with encouraging results.

In Part IV, we turn to more philosophical considerations. As brain-based and neuromorphic robots become more sophisticated, the possibility of truly intelligent machines is becoming a reality. The chapters in this section present frameworks for developing cognitive, or even conscious, robots. To reach this level of complexity, it will be impossible to program all the behaviors and intelligence into a robot. Some scientists are now looking at child development for inspiration in creating intelligent robots. Kaplan of EPFL in Switzerland and Oudeyer of INRIA-Futur in France present the concept of generic and stable kernels, and the notion of changing body envelopes to allow robots to develop on their own. A kernel can be thought of as a learning algorithm, and the envelope is the sensorimotor space that the body explores. The kernel and envelope idea may not only allow robots to develop body plans and fluid movements, it may also serve as a means to study our own development. Asada of Osaka University presents a framework for cognitive developmental robots. In particular, this chapter focuses on issues regarding the mirror neuron system for social cognitive development, and the development of a sense of self and others. Important to both developmental approaches is interaction with a rich real-world environment, as well as interaction with other agents. As an alternative to the developmental approach, Wagatsuma of the Kyushu Institute of Technology turns to dynamical systems to build neuromorphic robots. It is well known that brain oscillations and neural pattern generation are prevalent in the vertebrate brain. Moreover, it is thought that these dynamic patterns give rise to cognitive functions such as motor coordination, episodic memory, and consciousness. Wagatsuma presents a synthetic approach to studying the brain and uses embodied systems that emulate the brain's oscillatory dynamics. In the last chapter of this section, Fleischer and colleagues take on the ultimate goal of autonomous robotics: that is, machine consciousness. This group, which is led by Nobel laureate Gerald Edelman, has been studying consciousness for a number of years. Their chapter reviews prior work towards this goal, and presents a case for how to construct a conscious artifact, and how to test if the artifact is indeed conscious.

We feel strongly that the brain-based and neuromorphic approach will transform the field of autonomous robots to the point where we will have robots in our society that have the adaptability and intelligence that we attribute to biological systems. To paraphrase "Spiderman": with great power comes great responsibility.

The last section of the book deals with some very important ethical considerations. Bekey from the University of Southern California and his colleagues Lin and Abney from California Polytechnic State University discuss the ethical implications of intelligent robots and highlight the immediacy and urgency of the issue. They start by recapitulating Asimov's three laws of robotics and apply it to current military, healthcare, and other social robots. However, these laws fall short for present-day robotics, and the authors propose a hybrid approach toward achieving robot morality. In the final chapter, Shibata of Kanazawa University examines the ethical issue from a different point of view. He evaluates the argument that even though some people with autism lack a theory of mind or empathy towards others, we still need to grant these people the same rights as any member of the human race. Shibata then argues that we need to extend similar rights to intelligent robots if they have a theory of mind, even though they are not members of the human race.

The fact that *Neuromorphic and Brain-based Robotics* covers such a wide range of topics shows how unexplored this young field is at the present time. It is our sincere wish that scientists from other fields and a new generation of researchers find the chapters in this book thought provoking and inspiring. We have made our best effort to provide meaningful examples of prominent neuromorphic robots, present the philosophy behind this approach, and speculate on the construction of future robots with higher cognitive systems. These intelligent, brainy robots of the future will one day, very soon, be interacting and cooperating with human society. We strongly believe this research approach will advance science and society in positive and prosperous ways that we can only now imagine.

We hope you enjoy this survey of an exciting and groundbreaking area of research.

Cambridge University Press
978-0-521-76878-8 - Neuromorphic and Brain-Based Robots
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Excerpt
More information

Part II

Neuromorphic robots: biologically and neurally inspired designs