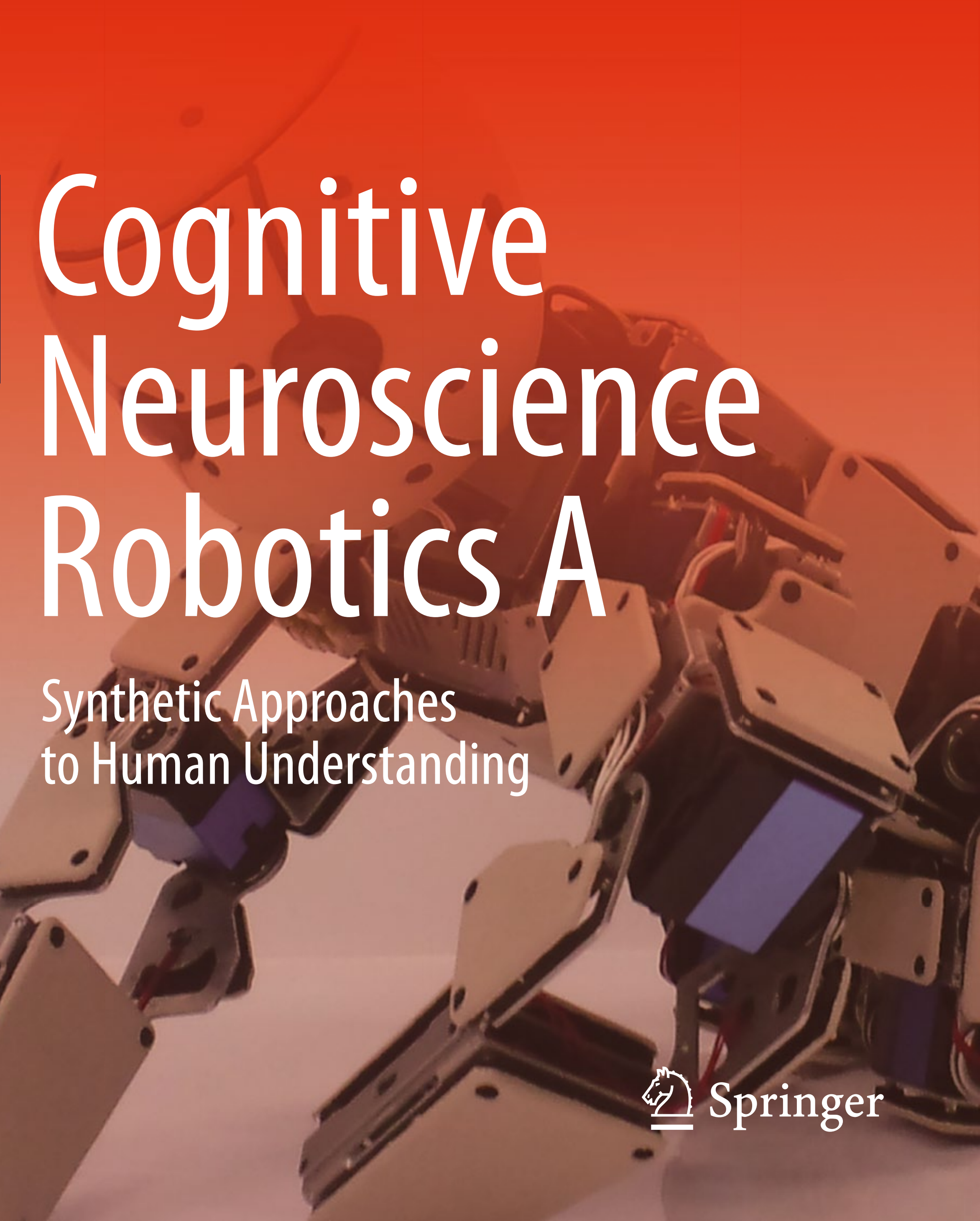
Masashi Kasaki · Hiroshi Ishiguro
Minoru Asada · Mariko Osaka
Takashi Fujikado *Editors*

Cognitive Neuroscience Robotics A

Synthetic Approaches to Human Understanding



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Preface

A variety of technologies are developing and making our society mechanized and computerized at an unprecedented pace, while the overall effects of this development on the human brain are not considered. Some examples of this development include exposure to a massive amount of information via computer networks and the widespread uses of cell phones and automobiles. At least some consequences of the development are not necessarily beneficial. It is highly plausible that our society, as it is today, places an excessive cognitive burden on the brains of children, the elderly, and even adults in the prime of life (see Fig. 1). In order to lead the development of technologies for every member of society in a healthy direction, it is necessary to develop new Information and Robot Technology (IRT) systems that can provide information and services on the basis of the understanding of higher human brain functions (or functions of the "cognitive brain").

In order to deeply understand the human brain functions and develop new IRT systems, Osaka University established the Center of Human-Friendly Robotics Based on Cognitive Neuroscience in 2009, with funding from the Global Center of Excellence (GCOE) Program of the Ministry of Education, Culture, Sports, Science and Technology, Japan. The Center integrates the following world-class research programs and studies at Osaka University, Advanced Telecommunications Research Institute International (ATR), and National Institute of Information and Communications Technology (NICT):

- World-famous human–robot interaction studies: Graduate School of Engineering and Engineering Science, Osaka University, ATR Intelligent Robotics and Communication Laboratories
- Japan's largest-scale program in cognitive psychology: Graduate School of Human Sciences, Osaka University
- World-recognized pioneering studies in brain science and brain machine interface: Graduate School of Medicine, Osaka University, and ATR Computational Neuroscience Laboratories, and NICT

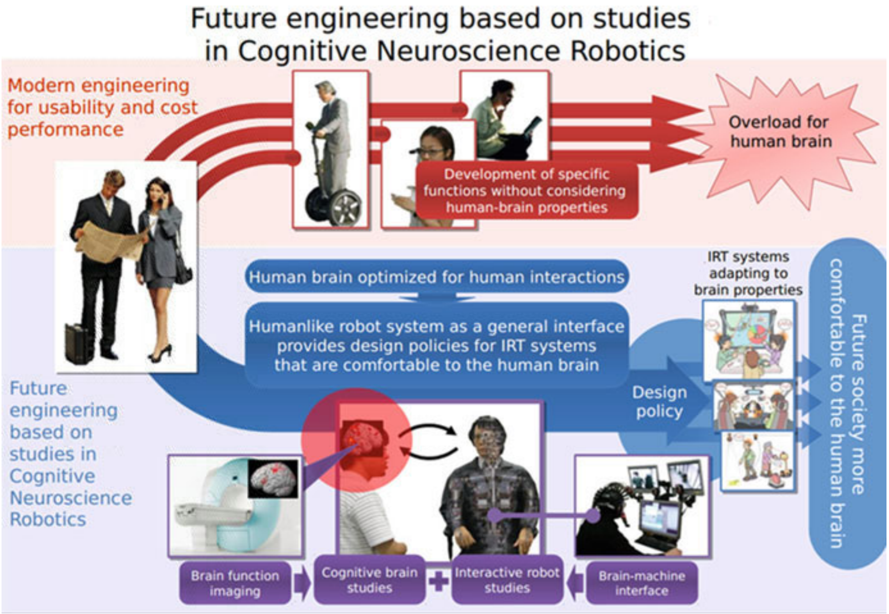

Fig. 1 Traditional engineering vs. future engineering

The Center pursues a new research and education area in which humanities and sciences closely collaborate with each other. Thus, the Center has reorganized education and research at the graduate schools of Osaka University and provided students and researchers a place to engage in the new research and education area. This new area is named cognitive neuroscience robotics.[1]

In more detail, cognitive neuroscience robotics addresses three interrelated research tasks, among others. The first task is to explore how higher brain functions [e.g., consciousness, memory, thinking, emotion, *kansei* (feeling), and so on] are involved in the use of IRT systems, by measuring brain activities with brain-imaging technology. This requires interdisciplinary studies between cognitive and brain sciences. The second related task is to investigate higher brain functions on the basis of brain functional imaging studies on brain function disabilities and studies on brain–machine interfaces (BMI). This requires interdisciplinary studies between brain science and engineering. The third task is to develop prototypes of human-friendly IRT systems and new hypotheses about the cognitive brain by combining studies relevant to the other tasks. In short, cognitive neuroscience robotics, with new technologies at hand, will establish a new understanding of the cognitive brain and develop prototype systems, to solve the problems with modern

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[1] The Center finished its proposed research under the funding from the GCOE program in 2014. The Center was then integrated into the Division of Cognitive Neuroscience Robotics, Institute for Academic Initiatives, Osaka University.

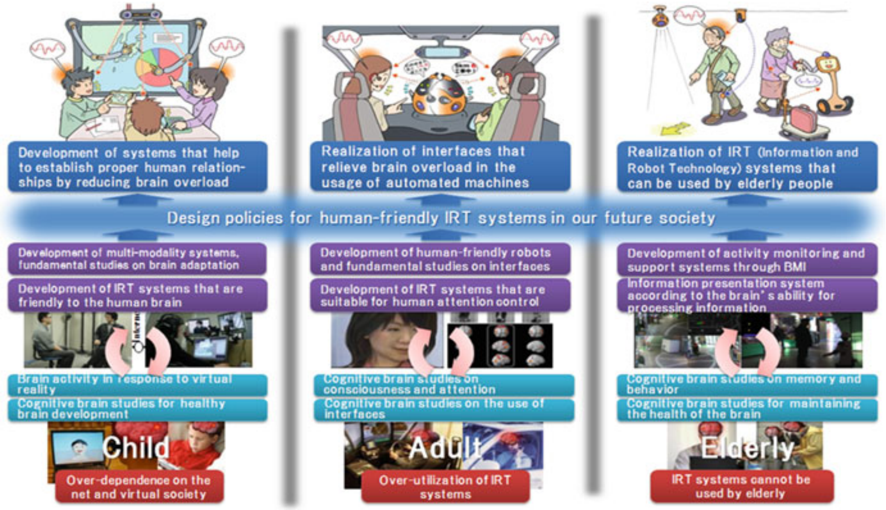

Fig. 2 Solutions by systems based on cognitive neuroscience robotics

mechanized society. Figure 2 shows a typical example of each of the three tasks of cognitive neuroscience robotics.

The Center consists of four interdisciplinary education and research groups. They are organized into a unified five-year education and research program dedicated to the tasks stated above.

- The Group for Establishment of Cognitive Neuroscience Robotics encompasses all research activities in the Center. It establishes the direction of the Center's education and research and aims to systematize the new area of cognitive neuroscience robotics, through scientific and philosophical considerations.
- The Group for Interdisciplinary Studies in Cognitive and Brain Sciences aims to reveal higher brain functions (the cognitive brain) with brain-imaging technology.
- The Group for Interdisciplinary Studies in Brain Science and Engineering develops brain–machine interfaces that directly connect the human brain with IRT systems.
- The Group for Development of Cognitive Brain Systems develops prototypes of future IRT systems that do not cause the overload of the human brain, as opposed to the existing IRT systems.

These interdisciplinary research groups include prospective researchers, engineers, and entrepreneurs. The Center offers them a graduate minor program of cognitive neuroscience. This program provides them with basics of cognitive neuroscience robotics and prepares them to address and accommodate the needs of the future society. Students enrolled in the minor program of cognitive neuroscience are required to take two courses: "synthetic approach to human understanding" and "cognitive brain science." Synthetic approach to human understanding and cognitive brain science are two aspects of cognitive neuroscience robotics, seen from the perspectives of robotics and cognitive science, respectively. Each course consists of a series of lectures given by representative researchers in the research groups.

This two-volume book is written as a textbook for prospective researchers in cognitive neuroscience robotics. Volume A, *Synthetic Approaches to Human Understanding, covers the* robotics aspect of cognitive neuroscience robotics and corresponds to the content of the course "synthetic approach to human understanding"; Volume B, *Analytic Approaches to Human Understanding*, covers the cognitive science aspect of cognitive neuroscience robotics and corresponds to the content of the course "cognitive brain science." The chapters of each volume are written by the lecturers of the corresponding course. The two volumes are jointly designed for young researchers and graduate students to learn what cognitive neuroscience robotics is.

We, the editors of this book, strongly hope that you, the reader of this book, will contribute to the development of our society by studying cognitive neuroscience robotics.

Lastly, we would like to convey our appreciation and gratitude to all authors of the individual chapters of this two-volume book. The main editor, Masashi Kasaki, read every chapter and provided detailed feedback to each author. His contribution to the book deserves special mention here.

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Chapter 1
Compliant Body as a Source of Intelligence

Koh Hosoda

Abstract No one denies that the brain is the main organ for cognition. However, the brain has evolved with the body. We cannot really understand how the brain works unless we understand the function of the body. In this chapter, we review several experimental examples of robots that have similar structures to humans and investigate the function of the body. It turns out that in order for a robot to achieve intelligent behavior, it is extremely important to have a compliant body with a muscular–skeletal structure.

Keywords Trade-off between the stability and controllability • Structural compliance • Biarticular muscle • Underactuated mechanism • Dynamic touch • Proprioceptive sensor • Passive dynamic walking • Coordination between joints (joint coordination)

1.1 Robot Design for Understanding Intelligence

How do we understand that body design is important for emerging intelligent behavior? To understand this, let us first consider two types of aircrafts: a control-configured vehicle (CCV) and a glider. A CCV is designed to enhance motion performance, but it has little aerodynamic stability. It cannot fly without control, but it is highly controllable. For example, it can change flight direction without changing the nose direction. A CCV can fly, because control theory and fly-by-wire technology are well developed. By contrast, a glider is designed for stable aerodynamics. It can fly without any control. However, its flight is totally governed by natural dynamics; thus, its controllability is relatively small. It cannot change the flight direction without changing the nose direction. Nor can it change flight speed so much. There is a trade-off between the stability and controllability of these aircrafts.

The trade-off for these aircrafts is similar to that between a motor-driven walking robot and a passive dynamic walker. When we apply motor control for a walking

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robot, we first design body motion so that it can walk stably and then derive the desired trajectory for each motor according to the designed body motion. The motor is controlled to track the desired trajectory, and as a result, whole-body motion is realized. Therefore, the whole-body motion of the robot can be easily altered by the designer; its controllability is large. However, the cost in terms of control is very high. Passive dynamic walkers are first introduced by McGeer (1990). Their walking is totally governed by natural dynamics. The dynamics of a walker is designed in such a way that it can walk down (or fall down, so to speak) a shallow slope. Because its walking down is passive and fully based on dynamics, it is difficult to change its walking behavior; however, it can walk without any control cost. Here again, there is a trade-off between stability and controllability.

How about human walking? If a person computes the desired trajectory of each joint and accordingly controls it, necessary computation is enormous. Can all computation be executed in the brain? If so, computation may engage most brain resources, and the person may not be able to execute other tasks while walking. On the other hand, if a person walks in a totally passive way, he/she can only walk down a slope and cannot cope with a flat plane or obstacles. Obviously, actual people walk in a way that incorporates the features of both stability and controllability; while people exploit body dynamics, they control their joints to some extent. In the artificial intelligence field, this is called a "diversity–compliance" or "stability–flexibility" trade-off (Pfeifer and Bongard 2007). We may not be able to understand the human intelligence required for walking if we only focus on either stability or controllability.

We may understand that human walking is neither completely controlled nor completely passive, but can we resolve the trade-off to realize a robot walking as adaptive as human walking? What is the common principle in human and robot bipedal walking? We must control the passivity: we must neither allow the robot to be completely passive nor allow it to control everything. The key idea is regulating *structural compliance*. The human body is compliant in a certain direction and rigid in another direction. A person intentionally controls the directionality of compliance so that he/she prepares for impact. Structural compliance is provided by the human muscular–skeletal and skin structure. By controlling structural compliance, we can shape global passive behavior. This will be the solution for the trade-off. In this sense, regulating structural compliance is very important for understanding human motion intelligence.

The actual human muscular–skeletal structure is very complicated and redundant. The number of control inputs—the number of muscles—is far larger than that of joints. This means that if we only focus on tracking desired trajectories, the number of solutions in terms of muscle excitation patterns is uncountable. This demonstrates the complexity of adaptive intelligence. To understand human motor intelligence, we must deal with the dynamic properties of the human body—the driving mechanism for generating intelligent behavior. In other words, we must focus on the muscular–skeletal system and soft skin. The most direct approach to this complicated system is to build a human-compatible body, let it work in a real environment, and observe how it functions. In this chapter, we will identify several challenges when we try to understand human adaptive behavior by building human-equivalent soft bodies.

Structural compliance is also important for physical sensation of humans and robots. If a human or robot uses vision or hearing sense, the human or robot can observe the environment without physically interacting with it; they can remotely observe the environment. However, if the human or robot uses touch to probe the physical environment, the interaction will involve both action and reaction. If a body is completely rigid, it cannot sense any physical property that can be obtained through touch. (Imagine that a force sensor has a certain elastic element where we can put strain gauges for measuring exerted force. If it is completely rigid, it cannot sense force.) By changing the structure of body compliance, we can control information flow from outside. Thus, the following question arises: how do humans regulate this structured compliance?

In what follows, we first introduce a very important engineering tool for understanding human's embodied intelligence—pneumatic artificial muscles (1.2). Then, we introduce an anthropomorphic robot arm driven by a humanlike muscular–skeletal system (1.3) and demonstrate that body compliance enables dynamic movement (1.4), dynamic touch (1.5), and dexterous manipulation (1.6). We also introduce passive-dynamics-based walking robots (1.7) and demonstrate that body compliance enables dynamic walking (1.8), floor detection (1.9), and dynamic jumping (1.10).

1.2 Pneumatic Artificial Muscles

A pneumatic artificial muscle is an engineering tool for realizing structural compliance equivalent to that of human's. Many prototypes and commercial products of artificial muscle exist. In Fig. 1.1, we show some pneumatic artificial muscles, called "McKibben pneumatic artificial muscles"; each muscle consists of a gum chamber and a covering plastic sleeve. When we supply air through the tube,

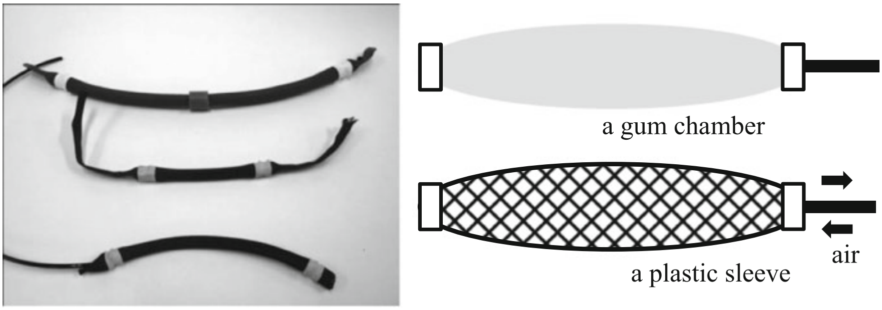

Fig. 1.1 McKibben pneumatic artificial muscles