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HUMANOID ROBOTICS and NEUROSCIENCE

SCIENCE, ENGINEERING and SOCIETY

Edited by Gordon Cheng

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Series Preface

The *Frontiers in Neuroengineering* series presents the insights of experts on emerging experimental techniques and theoretical concepts that are or will be at the vanguard of neuroscience. Books in the series cover topics ranging from electrode design methods for neural ensemble recordings in behaving animals to biological sensors. The series also covers new and exciting multidisciplinary areas of brain research, such as computational neuroscience and neuroengineering, and describes breakthroughs in biomedical engineering. The goal is for this series to be the reference that every neuroscientist uses to become acquainted with new advances in brain research.

Each book is edited by an expert and consists of chapters written by leaders in a particular field. The books are richly illustrated and contain comprehensive bibliographies. The chapters provide substantial background material relevant to the particular subject.

We hope that, as the volumes become available, our efforts as well as those of the publisher, the book editors, and the individual authors will contribute to the further development of brain research. The extent to which we achieve this goal will be determined by the utility of these books.

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Series Editor

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The Editor

Gordon Cheng holds the Chair of Cognitive Systems, Founder and Director of Institute for Cognitive Systems, at the Technical University of Munich. From 2002–2008, he was the Head of the Department of Humanoid Robotics and Computational Neuroscience, ATR Computational Neuroscience Laboratories, Kyoto, Japan. He was the Group Leader for the newly initiated JST International Cooperative Research Project (ICORP), Computational Brain. He has also been designated as a Project Leader/Research Expert for the National Institute of Information and Communications Technology (NICT) of Japan. He is also involved (as an adviser and as an associated partner) in a number of major European Union projects.

He held fellowships from the Center of Excellence (COE), Science and Technology Agency (STA) of Japan (1998–2002). Both of these fellowships were taken at the Humanoid Interaction Laboratory, Intelligent Systems Division at the Electro Technical Laboratory (ETL), Japan. At ETL he played a major role in developing a completely integrated humanoid robotics system. He received his Ph.D. in systems engineering (in 2001) from the Department of Systems Engineering, The Australian National University, and his Bachelor and Master degrees in computer science (respectively in 1991 and 1993) from the University of Wollongong, Australia. He has extensive industrial experience in consultancy as well as contractual development of large software systems. From 1994–2001, he was also the Director of G.T.I. Computing, a company he founded, which specializes in networking and transport management systems in Australia.

His research interests include humanoid robotics, cognitive systems, neuroengineering, real-time network robot control, brain–machine interfaces, biomimetics of human vision, computational neuroscience of vision, action understanding, human–robot interaction, active vision, mobile robot navigation, and object-oriented software construction.

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Section I

Humanoid Robotics Perspective to Neuroscience

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1 Humanoid Robotics and Neuroscience: Science, Engineering, and Society

Gordon Cheng

CONTENTS

1.1 INTRODUCTION

Ever since the dawn of civilization, we as humans have been fascinated with machines and devices that can replicate aspects of biology, in particular of ourselves. Some are created for our entertainment, some to facilitate us in our daily lives, and historically speaking some were even created for imitating the power of gods (religious relics) [1]. The themes of these developments have gone in and out of trends in various forms, but the most fundamental issues were to explore points toward the eventuation of robotics as we know it today.

We are on the verge of a new era of rapid transformations in both science and engineering, a transformation that brought together technological advancements in a fusion that shall accelerate both **science** and **engineering**. This new transformation brings together scientists working under a new direction of robotic research.

The utility of robots holds great promise not only in industrial automation; more recently it has also been taken on by neuroscientists as a tool to aid in the discovery of mechanisms in the human brain. In particular, with the emergence of numerous advanced humanoid robots, unlike usual robotic systems, these are highly sophisticated humanlike machines equipped with humanlike sensory and motor capabilities. These robots are now among us, contributing to our scientific endeavors.

Aiming at better assisting mankind has motivated engineers to look more closely at other scientific findings for the creation of innovative solutions that could better co-exist in our common **society**.

1.1.1 Our Research Paradigm

In essence, here we advocate three essential interconnecting themes in our research paradigm:

- In *science:* Building a humanlike machine and the reproduction of humanlike behaviors can in turn teach us more about how humans deal with the world, and the plausible mechanisms involved.
- In *engineering:* Engineers can gain a great deal of understanding through the studies of biological systems, which can provide guiding principles for developing sophisticated and robust artificial systems.
- For *society:* In so doing we will gain genuine knowledge toward the development of systems that can better serve our society.

Such an approach will examine in depth various issues that go beyond the pure engineering of a robot and will require the integration of multiple disciplines in exploring and exploiting what has been learned from other fields such as philosophy, neuroscience, psychology, and physiology among others. It is foreseeable that this multidisciplinary integration approach will examine in depth:

- How do humans handle all different types of interaction with ease and in such a competent manner?

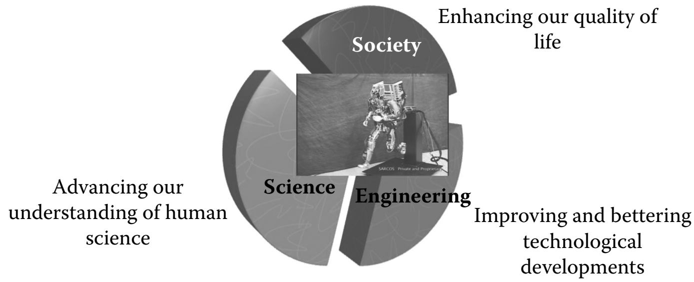

FIGURE 1.1 Research paradigm: Science, engineering, and society. See color insert.

- How can such a rich system be built?
- What are the underlying mechanisms?
  - What are the underlying processes and controls?
- How can we benefit from this approach?

1.1.2 Robots in the Real World

Recently robots have been moving off the factory floors and into our homes. Possibly one day these robotic systems will help us in our daily lives, also as ideal research tools. During the late 1990s a revitalization of interest in the building of humanlike robots has emerged. This resurgence of interest has produced a vast number of spectacular humanoid systems. Here we highlight some of these recent systems.

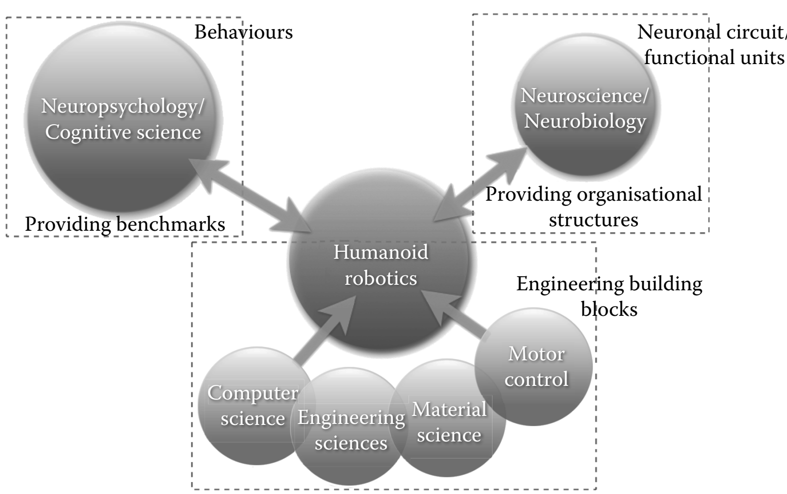

FIGURE 1.2 A multidisciplinary integration approach bringing together robotics and neuroscience.

FIGURE 1.3 SONY robotic dog, AIBO. (Courtesy of SONY. With permission.)

1.1.2.1 Entertainment Robots

Electronic SONY was one of the biggest manufacturers who introduced one of the first devices for home robot entertainment. In 1999, SONY introduced a four-legged doglike robot, AIBO, into the mass market as companions for people. These small-size entertainment (see Figure 1.3) robots have enjoyed worldwide acceptance. In the 2000s, SONY introduced a humanlike robot as the next generation of entertainment robots to the world (see Figure 1.4). It was a highly sophisticated integrated system, equipped with stereo cameras for eyes, microphones for ears, and an array of capabilities including walking and dancing [2].

Animatronics, one of the first nonindustrial companies in the area of animatronics, and entertainment companies such as Disney and MGM Studios are just a few who

FIGURE 1.4 SONY humanoid robot SDR-4. (Courtesy of SONY. With permission.)

FIGURE 1.5 Iguana, an animatronics entertainment robot. (Courtesy of Stephen C. Jacobsen, SARCOS. With permission.). An animatronics character in the form of an iguana, operates on a daily basis at the RC Willey Restaurant.

have utilized robotic technology within part of the venue to entertain all ages. One active group that has been supplying sophisticated robotic systems is the Utah company SARCOS. Their range of development includes full-body animatronics figures that can produce realistic human motions. They have also developed robotic animals from insects, singing birds, and iguanas (see, e.g., Figure 1.5) to full-size human figures.

A SARCOS humanoid figure (see Figure 1.6) [3] was designed specifically for the FORD Motor Company in 1995; this highly sophisticated system traveled to motor shows across North America and Europe from 1995 to 1997.

1.1.3 Humanoid Robots in Research

In this section we present some existing humanoid systems in research and briefly outline some of their approaches and achievements.

In December 1996, one of the highest impacts to robotics in recent times was made by the Japanese motor company Honda Motor Co., Ltd.: the release and announcement of a 15-year project which produced a full-size humanoid robotic system (see Figure 1.7) that was able to walk autonomously and climb stairs [4, 5]. This level of achievement set a standard for the engineering of highly sophisticated humanoid robots for years to follow.

1.1.3.1 Humanoid Service Robots

One avenue of humanoid research has been considering humanoids as ideal service robots. Taking the view that much of our everyday environment has been specifically designed for the use of humans, these humanlike robots would ideally be suitable for performing daily chores usually done by humans. This type of robot has been considered to be the most suitable to assist mankind with daily activities.

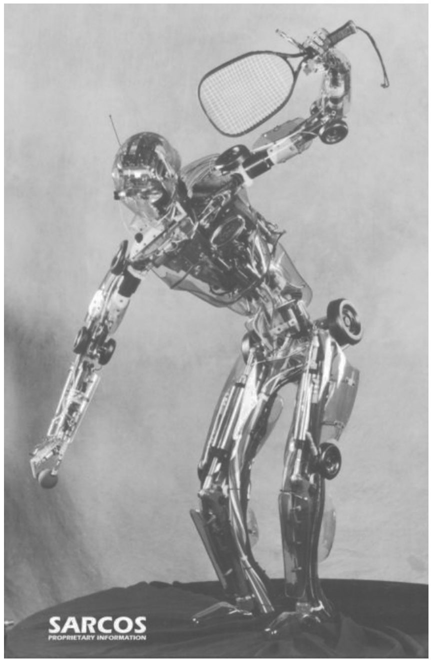

FIGURE 1.6 The FORD. (Courtesy of Stephen C. Jacobsen, SARCOS. With permission.)

The humanoid robot ARMAR (see Figure 1.8a) is a series of humanoid robots developed at the Karlsruhe Institute of Technology (KIT) [6, 7]. It was developed in targeting the introduction of such robots in the kitchen environment; for instance, it is even capable of loading dishes in a dishwasher.

The humanoid robot HERMES (see Figure 1.8b), developed by the Institute of Measurement Science, Bundeswehr University Munich, Germany [8, 9] provided another interesting aspect of service robots; one of the primary aspects of this particular system is that they aim for reliability. This system is able to text-to-speech interface. The AMI humanoid robot from the Korea Advanced Institute of Science and Technology (KAIST) [10] is a humanoid that is capable of a few household tasks, such as vacuuming (see Figure 1.8c).

At a further extreme both the Japanese and the Korean governments have decided to support projects related to humanoid robots that can facilitate society. A five–year project supported by the Ministry of Economy, Trade and Industry (METI) through the New Energy and Industrial Technology Development Organization (NEDO) of Japan, the Humanoid Robotics Project (HRP) was established to investigate possible "applications" for humanoid robots. They set out to examine five scenarios: (1) maintenance tasks of industrial plants, (2) teledriving of construction machines, (3) security service at home and office, (4) taking care of patients, and (5) cooperative works in the open air [11, 12]. The total robotic system was designed and integrated by Kawada Industries, Inc. together with the Humanoid Research Group of the National Institute of Advanced Industrial Science and Technology (AIST) [13].

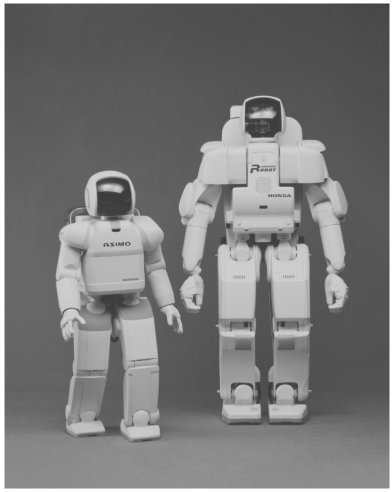

FIGURE 1.7 Humanoid robots P3 and ASIMO (Advance). (Courtesy of HONDA. With permission.)

The NASA Johnson Space Center in the United States is developing a humanoid upper body robot for use in space. They have designed the humanoid robot, Robonaut [14]. The primary objective of this system is to perform extravehicular activity (EVA). This sets the scene for future service robots in space.

1.1.3.2 Humanoid Robots as Research Tools

Although most robotic systems presented here are from research laboratories, many of them aim not just to build humanoid robots for the sake of constructing better machines. A number of these research laboratories are investigating issues beyond

FIGURE 1.8 Service-style humanoid robots. (a): ARMAR. (Courtesy of Tamim Asfour. With permission.); (b) HERMES. (Courtesy of Rainer Bischoff. With permission.); (c) AMI humanoid robot. (Courtesy of Hyun S. Yang, KAIST. With permission.)

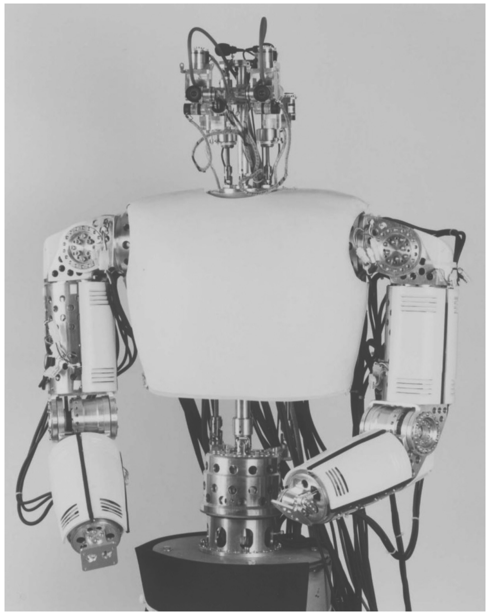

FIGURE 1.9 The ETL-Humanoid system. (Courtesy of Yasuo Kuniyoshi. With permission.) See color insert.

the engineering of systems; exploration is also underway in areas such as intelligent/cognition as well as basic science (thus, the research paradigm of "understanding through creating").

1.1.3.3 Cognition and Social Interaction

The MIT project, COG [15], was one of the first and noticeable groups that proposed to set out with the ambition of creating a humanoid robot that exhibits various aspects of "cognition" [16], ranging from basic visual and auditory attention [17], through various aspects of childlike development [18]. Following a similar research approach, in the work of Kawamura et al., they have been gradually building a humanoid system that has similar cognitive ability to that of humans; their main goal is to develop a system that can support elderly patients [19].

Around the end of the 2000s, a multimodal interactive humanoid system was developed as a platform for the study of humanoid interaction [20]. The system, ETL-Humanoid (see Figure 1.9), was developed at the ElectroTechnical Laboratory (ETL) in Japan during the period of 1996–2001 [21]. This system was designed as a research tool for exploring general principles of intelligent systems through interaction with the changing world. Interactions involving visual, auditory, and the physical all form part of its integration; one noticeable work yielded complex and meaningful interaction with a human through exploiting a continuous sensory–motor cooperative–competitive integration architecture, which demonstrated continuous adaptivity, redundancy, and flexibility [22].

FIGURE 1.10 Babybot from the LiraLab. (Courtesy of Giorgio Metta. With permission.)

At the same time, the LiraLab at the University of Genoa, Italy was attempting to combine ideas from human development in the construction of their humanlike system, Babybot (see Figure 1.10) [23]. Their robot learns through stages of development to perform the basic task of reaching. One especially interesting feature of this system is that the vision processing is performed through the use of a log-polarlike CMOS camera, having pixels arranged in a configuration emulating that of the human retina, from the center to the periphery in dense to sparse pixel arrangements. This emulation shows that computation and information flow can be reduced, providing the same visual capabilities as these of a child. Their approach makes a detailed attempt in providing and demonstrating benefits of emulating details of biology in the development of a sophisticated human-like robot [24].

A noticeable followup to the Babybot project is the European project RoboCub. This integrated project aimed to develop a 3.5-year–old child-sized humanoid robot, the iCub (see Figure 1.11), for the study of cognition through its implementation of cognitive capabilities similar to those of a child [25]. Unlike many past projects, this 5-year–long project continued to provide iCub as a humanoid robotic platform for research; more than 20 iCub robots have been deployed in facilitating research worldwide.

1.1.3.4 Social Interaction

One noticeable work in the area of social interaction is by a group in Japan. Investigating the use of robots to interact with autistic children, their aim or wish is ultimately to draw out children with identifiable social defects and teach them to interact in more humanlike ways. The robot is called "Infanoid" (see Figure 1.12) [26] and was developed as a tool for this purpose. Preverbal communication in infants, that is, using nonverbal means (e.g., gaze, gestures, etc.), plays a crucial role in human communication development. Children with autism who show typical communication disorders cannot use these preverbal communication skills, which leads to serious impairment

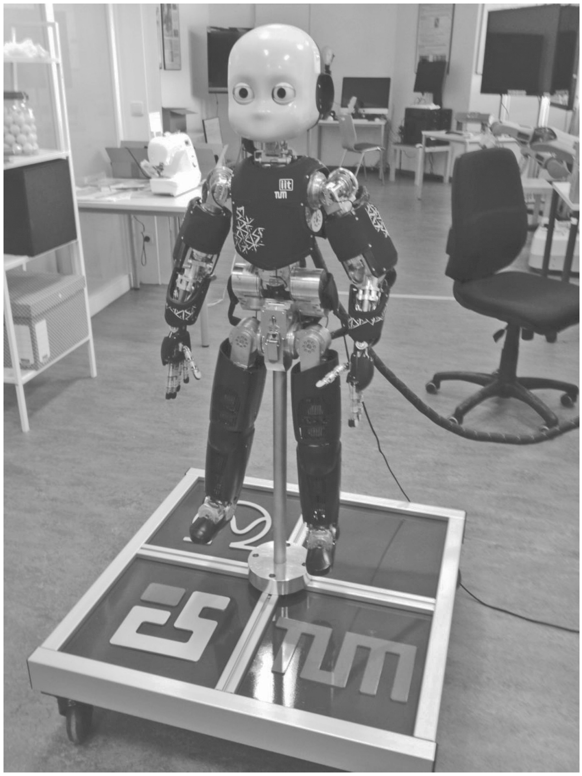

FIGURE 1.11 The iCub humanoid robot (iCub at the TUM-ICS lab). See color insert.

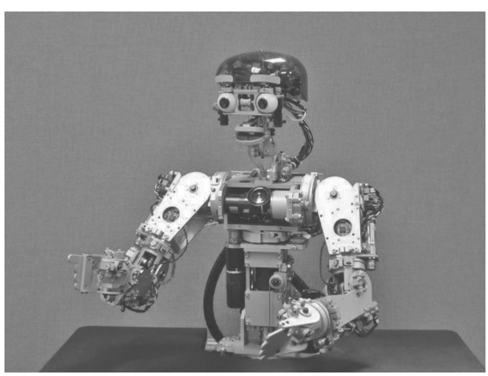

FIGURE 1.12 Infanoid. (Courtesy of Hideki Kozima. With permission.)

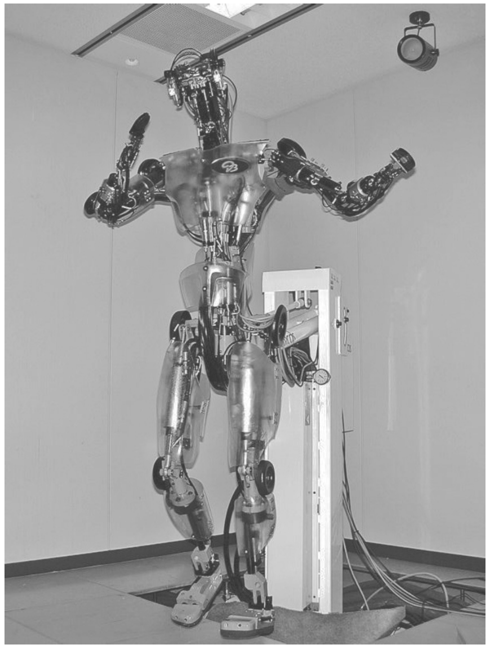

FIGURE 1.13 ATR humanoid robot, DB (co-developed with SARCOS during the JST Kawato Dynamic Brain Project). (Courtesy of Stefan Schaal. With permission.)

in social abilities and verbal communication. The aim of this ongoing project is to understand the mechanism/development of human communication.

1.1.3.5 Humanoid Robot in Neuroscience

The Advance Telecommunication Research Institute was the first to propose that a humanoid robot could actually contribute to neuroscience studies. In their work they demonstrated several aspects of humanlike learning, and were successful in applying these to humanoid robots [27]. The humanoid robot, DB (dynamic brain), was specifically developed for this purpose (see Figure 1.13). The success of this work set an important landmark in the application of scientific interchange between engineers and neuroscientists.

1.1.4 CB—Computational Brain

Following the guiding principles above, a 50-degrees-of-freedom humanoid robot, CB, computational brain, was realized. CB is a humanoid robot created for exploring the underlying processing of the human brain while dealing with the real world. We place our robotic investigations within real-world contexts, as humans do. In so doing, we focus on utilizing a system that is closer to humans in sensing, kinematics configuration, and performance.

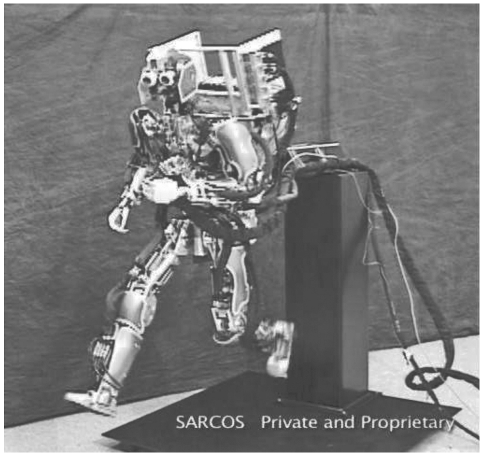

FIGURE 1.14 The humanoid robot CB (computational brain).

We present the real-time network-based architecture for the control of all 50 degrees-of-freedom. The controller provides full position/velocity/force sensing and control at 1 KHz, allowing us the flexibility in deriving various forms of control. A dynamic simulator is also presented: the simulator acts as a realistic testbed for our controllers, and acts as a common interface to our humanoid robots. A contact model developed to allow better validation of our controllers prior to final testing on the physical robot is also presented.

Three aspects of the system are highlighted in this chapter (1) physical power for walking; (2) full-body compliant control, physical interactions; and (3) perception and control, visual ocular–motor responses.

Our objective is to produce a richly integrated platform for the investigation of humanlike information processing, exploring the underlying mechanisms of the human brain in dealing with the real world. In this chapter, we present a humanoid robotic system, a platform created to facilitate our studies.

Our focus is toward the understanding of humans, more specifically the human brain, and its underlying mechanisms in dealing with the world. We believe that a humanoid robot that is closer to a human being will facilitate this investigation. Such a sophisticated system will impose the appropriate constraints by placing our exploration within the context of human interactions and human environments. As a result, a full-size humanoid robot CB (computational brain) was built to match closely the physical capability of a human, thus making it suitable for the production of a variety of humanlike behaviors, utilizing algorithms that originate in computational neuroscience.

1.1.4.1 Outline

The following sections describe the physical robotic system and the supporting software control architecture used in our research. We present experimentally three

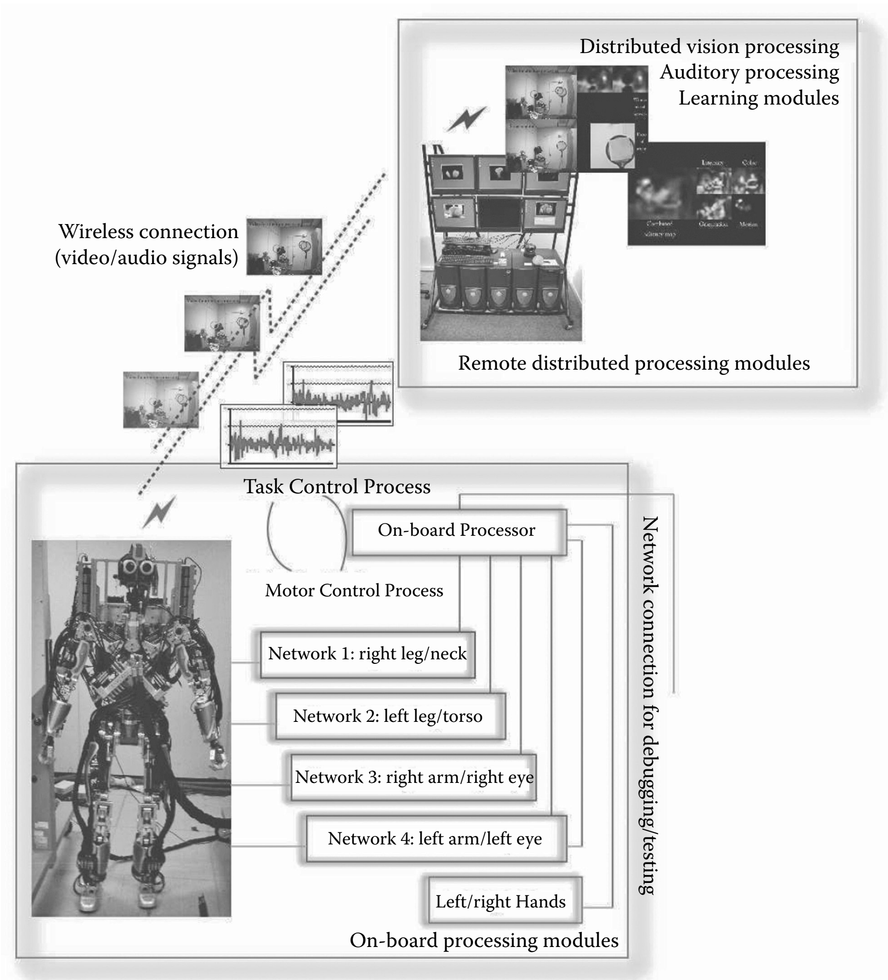

FIGURE 1.15 Overview of the CB research platform and setup, providing full support for local processing for robot sensing and motor control, also showing that demanding high-level processes are dealt with using remote distributed processors.

aspects of our system: (1) adequate performance; (2) force controllability; and (3) perceptual abilities of our humanoid system.

1.1.5 Research Platform—Hardware and Software Architecture

In this section, a presentation of the hardware and software architecture of our research platform, CB, is presented. An overview of the setup is depicted in Figure 1.15, Table 1.1 which, presents the overall technical specifications of the system and explains their corresponding biological counterparts.

TABLE 1.1
Overall Specification of Humanoid Robot—CB

Degrees of Freedom	50 in Total	
Actively compliant	Arms/Legs/Torso/Neck (34 DOFs)	Central body parts of the humanoid robot
Passively compliant	Fingers/Eyes (16 DOFs)	Forming two hands for manipulation
Weight	92Kg	
Height	157.5cm	Average person
Orientation sensors	2 × 6 DOF (translational and rotational)	Emulating the vestibular system
Foot force sensors	2 × 6 DOF (left and right)	Ground contact detection
Onboard computer	Arbor PC-104 plus Em104P-i7013/PM1400 1.4 GHz Intel Pentium-M Processor	Acting as the motor controller of the whole system, emulating the role of the spinal column
Cameras	2× ELMO MN42H 17mm O.D. (Peripheral)/2× ELMO QN42H 7mm O.D. (Foveal)	Emulating both the peripheral and foveal human visual systems
Microphones	2× SHURE Model MX180	Emulating human binaural hearing system

1.1.5.1 Humanoid Robot—CB

The humanoid robot CB was designed with the general aim of developing a system capable of achieving human capabilities, especially in its physical performance. CB, the physical system, is of general human form; the following sections present the basics of the system.

1.1.5.1.1 Mechanical Configuration

CB is a full-body humanoid robot. It is approximately 157.5 cm in height and approximately 92 kg in weight. It has an active head system with 7 degrees of freedom (2 × 2 degrees-of-freedom eyes, 1 × 3 degrees-of-freedom neck), 2 × 7 degrees-of-freedom arms, 2 × 7 degrees-of-freedom legs, 1 × 3 degrees-of-freedom torso, and 2 × 6 degrees-of-freedom hands (see Figure 1.3), 50 degrees of freedom in total (see Figure 1.1). The system has similar ranges of motion and physical performance as a human person (as guided by human factors studies [19]). The system is able to perform saccadic eye movements at up to 3 Hz (similar to that of humans). The hands (as shown Figure 1.3) have been developed to provide basic functionality such as grasping, pointing, and pinching.

1.1.5.2 Sensing Subsystems

The active head houses a set of inertial sensors (three-axis rotational gyro, three-axis translational accelerometer). They are used to emulate the human vestibular system (the inner ear), providing head orientation, as used for gaze-stabilization. An