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Full paper

CB: a humanoid research platform for exploring neuroscience

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Abstract—This paper presents a 50-d.o.f. humanoid robot, Computational Brain (CB). CB is a humanoid robot created for exploring the underlying processing of the human brain while dealing with the real world. We place our 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. We present the real-time network-based architecture for the control of all 50 d.o.f. 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 paper: (i) physical power for walking, (ii) full-body compliant control—physical interactions and (iii) perception and control—visual ocular-motor responses.

Keywords: Humanoid robotics; biped locomotion; humanoid interaction; vision attention; biologically motivated vision; control architecture; dynamic simulation; contact modeling.

1. INTRODUCTION

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

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1.1. Research landscape

Major projects on humanoid robots are still being actively pursued. Honda with their landmark work on P2, then P3 and recently ASIMO [1] have impacted upon the recent trends in robotics research. The HRP project was a major project that was established to investigate the feasibility of applications for humanoid robots [2]. The SONY QRIO project was targeted to produce robotics systems suitable for entertainment purposes [3].

Activities at the University of Tokyo have produced a number of humanoid robots, e.g., H5, H6 and H7, which were designed for walking and, recently, balancing while reaching [4]. The Waseda University group developed the WABIAN series robots, e.g., the new humanoid robot, WABIAN-2, designed for walking with/without walk-assist machines [5]. Following much of the initial success in humanoid robotics research, Johnnie, produced by the TUM group in Germany [6], and the KHR series robots from KAIST in Korea [7, 8] are examples of humanoid robots focusing on biped locomotion research.

Much of the initial research in humanoid robotics to date has been geared toward bipedal walking. More recently, works on furthering behaviors of these robots have been considered, noticeably ASIMO in user interactions and HRP in producing various applications (e.g., operating a backhoe/assisting in daily living) are just some of the recent successful example applications for humanoid robots. The group at the University of Karlsruhe focuses on designing and using upper-body humanoid robots for service tasks [9]. The prime focus of these systems has been toward the discovery of an application that is suitable for humanoid robots.

With regard to intelligent systems research, the earlier works of Brooks *et al.*, utilizing an upper-body humanoid robot, COG, aimed at studying cognitive abilities [10], producing a number of real-world human-like behaviours on COG [11]. The work of Kuniyoshi *et al.* is another example; they take the view that intelligent behaviors can emerge via an integrative system and its interaction with the world [12–14]. The recent work of Sandini *et al.* [15] has been utilizing studies of developmental psychology and neuroscience research as a guide in developing a child-like humanoid robot system, Robot-cub.

The recent work of Ishiguro *et al.* [16] places a strong emphasis on physical appearance in the development of their 'androids' and they examined the effects of human–robot interaction with such human-like robots [17].

In our investigation, we wish to utilize a richly integrated system for investigating human-like behaviors. Our CyberHuman project was initiated at the behavioral level to explore ways to reproduce human-like behaviors [18]. Our research follows on from these previous studies, extending beyond the reproduction of human-like behaviors, to account in greater detail for the underlying processes.

1.2. Motivations—our approach

As our research interests fall in line with the notion of 'understanding through creating'. Two essential aspects motivate our approach:

- Engineering. Engineers can gain a great deal of understanding through studies of biological systems, which can provide guiding principles for developing sophisticated and robust artificial systems;
- Scientifically. Building of a human-like machine and the reproduction of human-like behaviors can in turn teach us more about how humans deal with the world, and the plausible mechanisms involved.

Our focus is towards 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—Computational Brain (CB, developed by SARCOS)—was built to closely match the physical capability of a human, thus making it suitable for the production of a variety of human-like behaviors, utilizing algorithms that originate in computational neuroscience (Fig. 1).

1.3. Outline

The following sections describe the physical robotic system and the supporting software control architecture used in our research. We present experimentally three aspects of our system: (i) adequate performance (Section 3.1), (ii) force

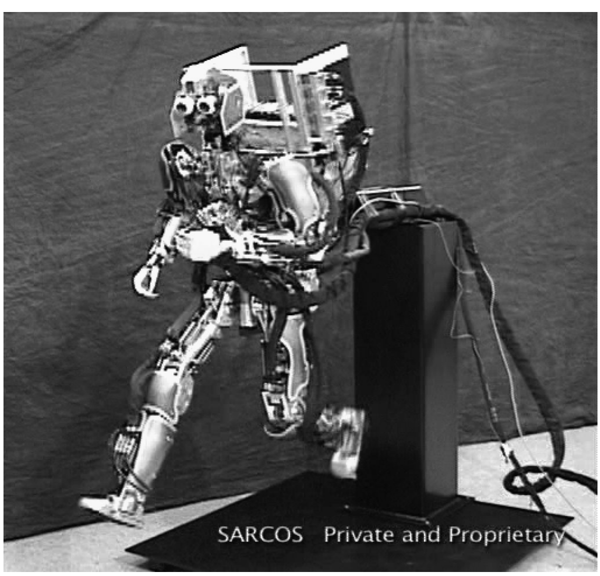

Figure 1. Humanoid Robot—CB (built by SARCOS).

controllability (Section 3.2) and (iii) perceptual abilities of our humanoid system (Section 3.3).

2. 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 Fig. 2. Table 1 presents the overall specifications of the system.

2.1. Humanoid robot—CB

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

2.1.1. 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 d.o.f. (2 × 2-d.o.f. eyes, 1 × 3-d.o.f. neck), 2 × 7-d.o.f.

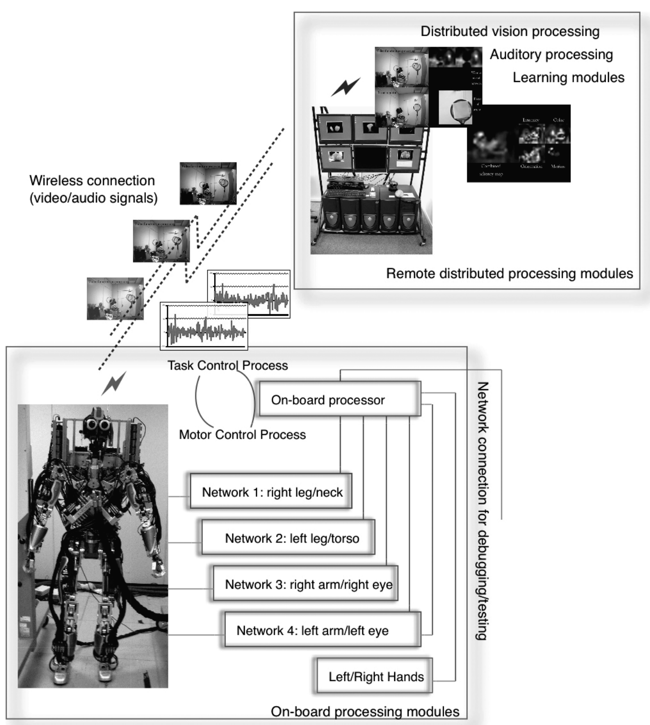

Figure 2. Overview of our research platform and setup.

Table 1.
Overall specification of CB

Degrees of freedom	50 in total
Actively compliant	arms/legs/torso/neck (34 d.o.f.)
Passively compliant	fingers/eyes (16 d.o.f.)
Weight	92 kg
Height	157.5 cm
Orientation sensors	2 × 6 d.o.f. (translational and rotational)
Foot force sensors	2 × 6 d.o.f. (left and right)
Onboard computer	Arbor PC-104 Plus Em104P-i7013/PM1400 1.4 GHz Intel Pentium-M processor
Cameras	2 × Elmo MN42H 17 mm OD (peripheral)/ 2 × Elmo QN42H 7 mm OD (foveal)
Microphones	2 × Shure model MX180

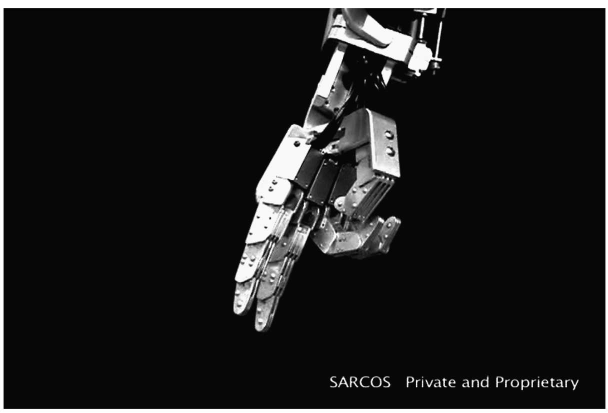

Figure 3. Five-finger humanoid robot hand with 6 d.o.f. (built by SARCOS).

arms, 2 × 7-d.o.f. legs, 1 × 3-d.o.f. torso and 2 × 6-d.o.f. hands (see Fig. 3), making 50 d.o.f. in total (see Fig. 1). The system has similar ranges of motion and physical performance as a human person (as guided by a human factors studies [19]). The system is able to perform saccadic eyes movements at up to 3 Hz (similar to that of humans). The hands (as shown Fig. 3) have been developed to provide basic functionality, such as grasping, pointing and pinching.

2.1.2. Sensing subsystems. The active head houses a set of inertial sensors (three-axis rotational gyro and three-axis translational accelerometer). They are used to emulate the human vestibular system (the inner ear), providing head orientation, as used for gaze stabilization (see Section 3.3). An additional inertial sensor is installed at the hip to provide angular velocity/translational acceleration near the center of mass of the whole body, used to provide the overall orientation of the system. The visual system is made up of two cameras per eye—a peripheral (wide-angle view) and a foveal (narrow view) camera are installed on each eye to emulate the visual acuity of the human visual system. Stereo microphones have also been installed to provide hearing to the robot. Images from the video cameras and the auditory signals are transmitted over high-speed wireless communication to a network of PCs for perceptual processing (discussed in Section 2.4).

2.1.3. Proprioceptive sensing. Proprioceptual information plays a key role in human motor control, informing the limbs and higher-level cortices of critical information in carrying out suitable action. Our system is equipped to support various forms of control to account for interactions and position/velocity/torques sensing is provided at the key joints for proper active compliant control (arms/legs/torso/neck—34 d.o.f.). Foot force sensors are installed at the soles of each foot to provide information during ground contact and weight distribution, as it is critical for walking and balancing control. The uniqueness of this system over previous systems is that torque sensors are installed on the main joints of the system, i.e. the arms/legs, torso and neck, allowing joint-level active compliant possible.

2.2. Software control architecture

As depicted in Fig. 2, we developed a network-based architecture to better enable us to explore various levels of human-like processing on our humanoid system. It is divided into two: on-board low-level computing and higher-level perceptual processing.

2.2.1. On-board computing. The control of the robot is through an on-board PC-104Plus CPU stack with an Intel 1.4 GHz Pentium-M processor, which provides control and sensory feedback to all the joints, performed at a maximum rate of 1 kHz (for all 50 d.o.f.). The Motor Control process (a software module) gathers sensory data (joint position/velocity/force information, foot force sensors, gyro/accelerometer data) of the four internal network branches to each of the low-level joint controllers (as depicted in Fig. 2). A Task-level Control process (a software module) running on the local processor communicates with the Motor Control process to perform higher-level control functions (see Section 3). One external 100 Mbits/s Ethernet network connection is also provided for debugging and testing purposes. The on-board computer runs the ART-Linux operating system, a real-time version of the Linux, which retains all the standard functionality of Linux with the addition of real-time support [20]. The on-board processor is sufficient for walking control (Section 6) and force-based balancing control (Section 3.2). Any processing that requires substantial computations such as vision processing are performed remotely on a cluster of PCs (see next section).

2.3. Dynamic simulation and ubiquitous interface

Having a testbed is an essential element in conducting research, and for validating a variety of control strategies and algorithms for a complex physical system such as a humanoid robot. A realistic dynamic simulator has been developed for our humanoid robot (Ref. [21] and data not shown). The simulator serves two purposes: (i) realistic dynamic simulation, providing a realistic testbed for our controllers prior to experimentation on the real robot and (ii) ubiquitous interface, providing a transparent programming interface between the simulator and the real robot.

2.3.1. Realistic dynamic simulator. Our dynamic simulator serves as a realistic testbed for our controllers prior to experimentation on the real robot. One key aspect of the simulator is the development of a new contact model [21]. The contact model was developed to better facilitate evaluation of our controllers in a safe and consistent manner by quickly computing accurate contact interactions based on empirical estimates of real-world friction properties. Figure 4 shows our CB simulator.

The simulator provides kinematic and dynamic analyses for task control. It provides access to the robot's posture, link coordinate frames, dynamic Jacobians, zero moment point, etc., based on sensor data (see Table 2).

Modeling contact. Contact resolution methods have been extensively investigated to support our simulator [21]. In our CB simulator, an efficient contact handling method that applies Coulomb friction exactly has been developed [21]. It is important for humanoid robots to handle contact and friction forces accurately and efficiently in order to validate their controllers for real-world conditions. The method used in the CB simulator models contact between the humanoid's feet and a planar ground surface, and explicitly identifies the contact state of each foot. For a rectangularly footed biped, there are 361 possible contact states. Each foot may be contacting in one of 19 ways: at one of four vertices, one of four edges, with its face or not in contact at all. Active contacts may be static or dynamic.

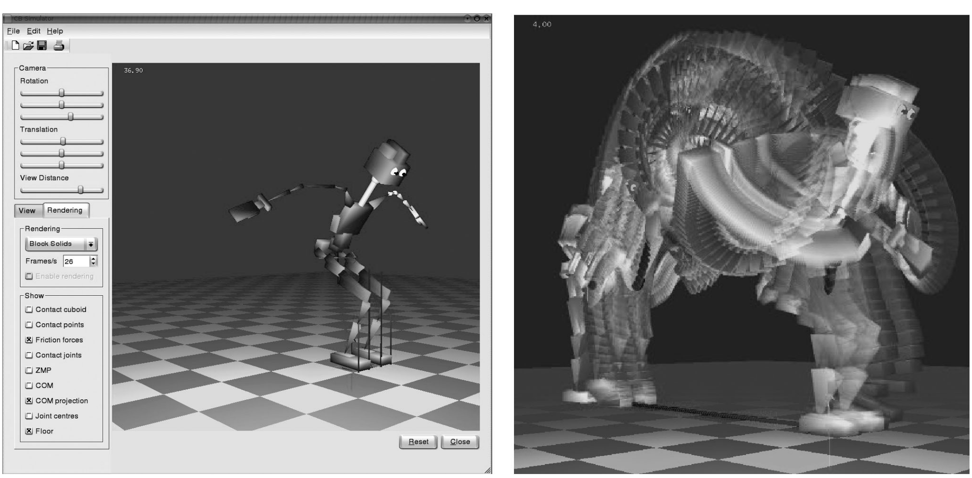

Figure 4. A snapshot of our dynamic simulator.

Table 2.
Accessible data within the simulator

Joint position	arms/legs/torso/neck/eyes (38 d.o.f.)
Joint torque	arms/legs/torso/neck (34 d.o.f.)
Joint position, velocity and torque control gains	arms/legs/torso/neck (34 d.o.f.)
Foot force contact	2 × 6 d.o.f. (left/right)
Contact points	8 × 3 d.o.f.
COM	3 d.o.f.
Zero moment point	3 d.o.f.
Friction parameters	2 d.o.f. (static and dynamic)
Link coordinate frames	38 homogeneous transform matrices
COM Jacobian	d.o.f. × 3 matrix
Contact point Jacobians	8 d.o.f. × 3 matrices

2.3.1.1. Friction parameters. These may be specified during simulation. Static friction is applied by incorporating the appropriate motion constraints into forward dynamics computations using Lagrange multipliers and dynamic frictions are integrated as additional forces. Measurements of the friction properties of CB's feet with various surfaces were conducted in order to provide an empirical basis for accurate simulation of the robot's contact interactions with its environment.

2.3.2. Ubiquitous interface. The simulator also acts as a common interface to our collection of humanoid robots. Controller code running a simulated robot can be executed identically on the corresponding real robot. This accords with the concept of a humanoid robotics platform described in Ref. [2], i.e., it provides a seamless control interface between the simulated and actual robot. Also, the provision of a ubiquitous control environment ideally facilitates an identical software interface to arbitrary robots. This ensures the portability and generalized utility of control software. In our system we provide this functionality by using an identical network interface for communication between the Motor Control process (described in Section 2.2.1) and the simulator. Figure 5 illustrates the general idea of our ubiquitous interface.

2.4. An architecture for emulating human-like processing

The overall structure of the system has been developed to facilitate the emulation of human information processing. The distributed architecture we proposed is motivated by neurological studies of the visual cortices, e.g., Van Essen and De Yoe [22]. These findings showed in great detail that processing in the brain is a well-organised structure, with connections and pathways. In our system, we emulated this aspect of this organizational structure with a network of computers. The cluster of PCs is connected via a series of 1-Gbit/s Ethernet networks. We proposed a framework utilizing the UDP protocol with data streamed from one process to another. The processing on each PC can range from the most basic

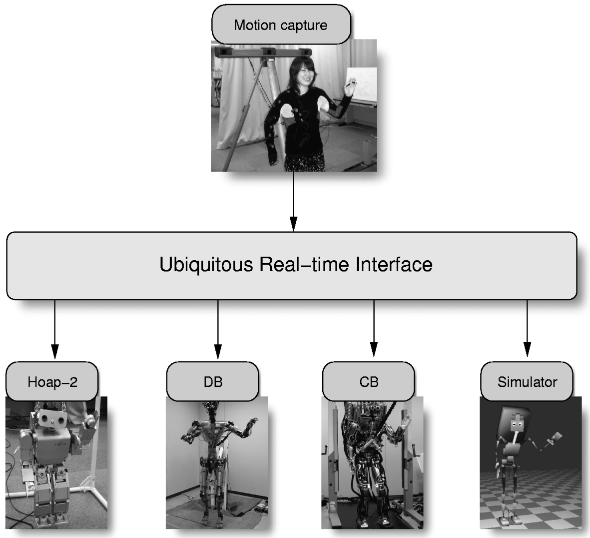

Figure 5. General concept of our ubiquitous interface.

(e.g., color extraction, edge filtering, etc.) to higher level (e.g., visual tracking, recognition, etc.). The sophistication of the system can increase quite rapidly simply through connecting the processing outputs of simpler elements to the inputs of more advanced processing elements in a bottom-up manner. Manipulation of the lower-level processes can also be performed in a top-down fashion. This framework will provide the capability to explore a greater range of cognitive architectures. Modules from spatial hearing to learning modules (SOM, R-L learning, Associative Memory) have also been developed to support our studies.

The effectiveness of this distributed architecture has been demonstrated with the development of a visual attention system [23], a real-time human hand-tracking system [24] and visual ocular–motor control for our humanoid system (described in Section 3.3).

3. HUMAN-LIKE BEHAVIOURS

In this section, we present experimentally three aspects of our system: (i) physical power for walking, (ii) full-body compliant control—physical interactions and (iii) perception and control—visual processing and ocular-motor responses.

3.1. Human-like performance—walking

To examine human-like walking, we have investigated a number of biologically inspired walking algorithms [25–27]. Here, we present one central pattern generator (CPG)-based locomotive controller that managed to produce naturally looking walking movements on our humanoid robot.

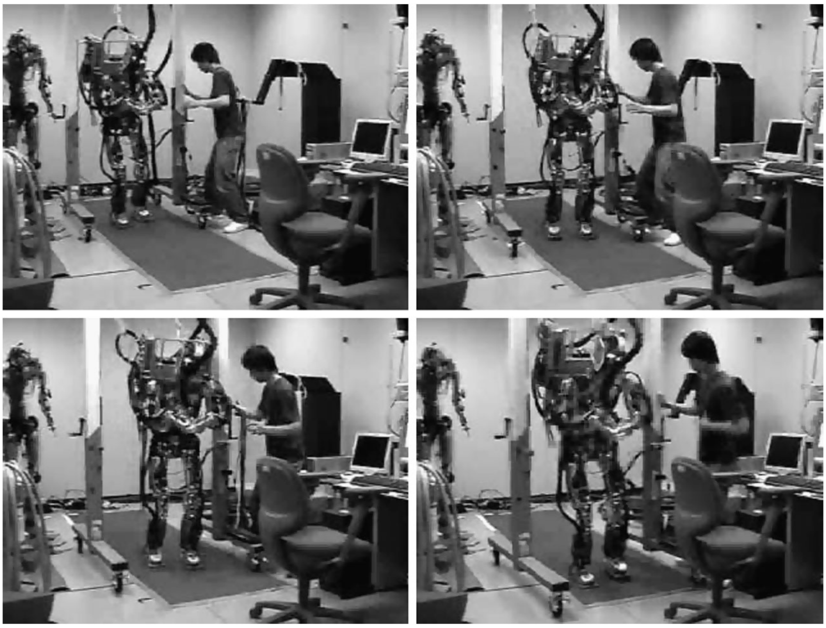

Figure 6. Walking utilizing a biologically based controller.

In the experiment shown in Fig. 6 we demonstrate that a humanoid robot can step and walk using simple sinusoidal desired joint trajectories with their phase adjusted by a coupled oscillator. The center of pressure and velocity are used to detect the phase of the lateral robot dynamics. This phase information is then utilized to modulate the desired joint trajectories, thus enabling us to generate successful stepping and walking patterns [28]. This walking demonstration shows that our system has adequate performance in supporting the full body.

3.2. Compliant control: three-dimensional (3-D) balancing and physical interactions

Force control or compliant control plays a key role in the ways humans interact with the world. This is well supported by biomechanical studies [29]. Humans control the stiffness of their limbs in dealing with contacts while performing appropriate tasks. This is also supported by the passivity of non-linear control theory [30]. We developed a controller to perform 3-D force-based control of CB.

One of the controllers we developed is a full-body contact force controller with gravity compensation [31]. The gravity compensation is possible only for a force-controllable humanoid like CB; an example of the force-tracking performance of the system is shown in Fig. 7. This makes the robot passive with respective to any external force applied to arbitral contact points and, hence, results in compliant full-body interaction. The additional contact force allows the robot to generate desired ground reaction forces and other necessary interaction forces. For example, if we

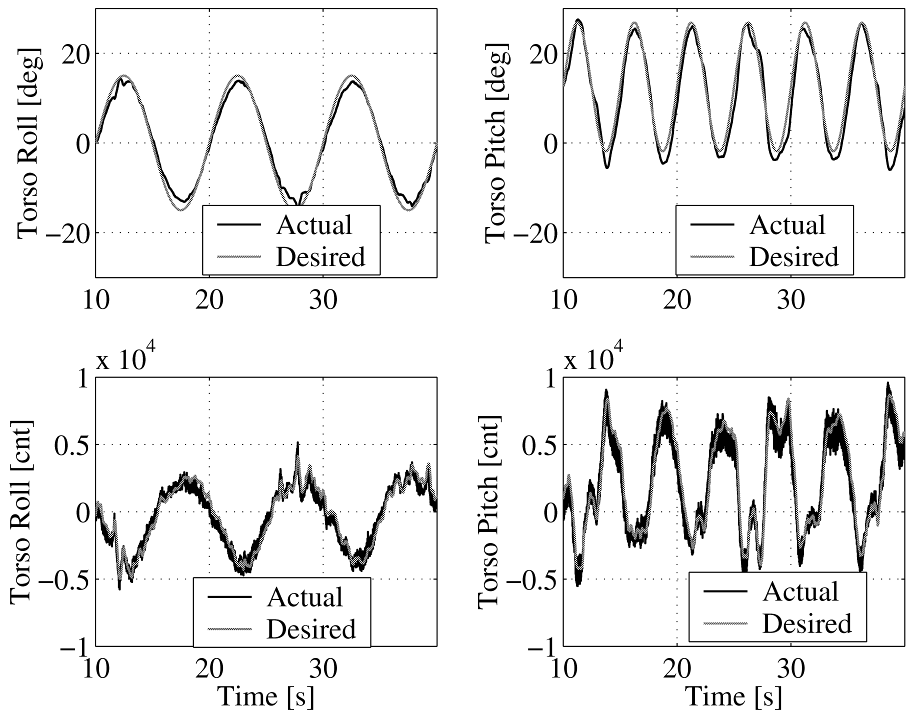

Figure 7. Force-based tracking performance of our force-based controller during 3-D balancing. Upper graphs show the angle commands and the responces of the torso joints (‘figure of 8’ trajectory) while maintaining balance. Lower graphs show the corresponding force inputs and the ‘Actual’ force feedback.

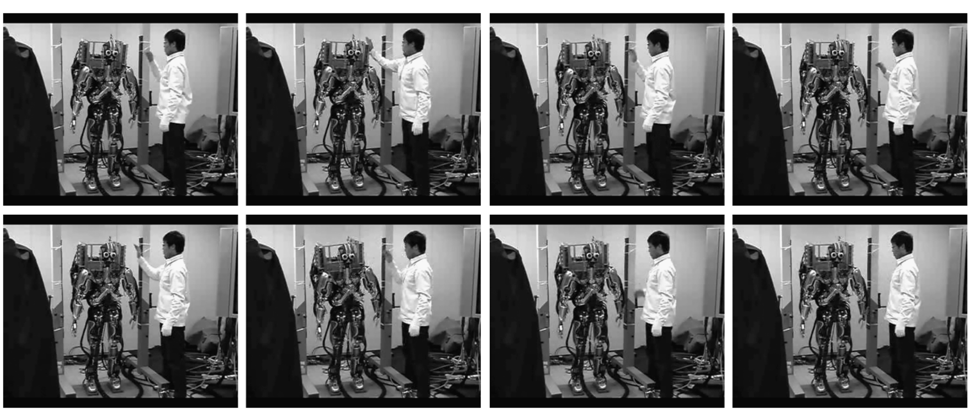

Figure 8. Physical interactions—multiple abrupt pushes by a person while the robot maintains balance.

define the desired ground reaction force as a feedback to the center of mass, then full-body 3-D balancing is easily realized. Figure 8 shows such an example, where the robot is being abruptly pushed on the upper-left shoulder. The robot was able to recover and maintain balance. With the same force control framework, the robot performed squatting, force tracking to external forces and position tracking while keeping balance [31].

3.3. Perception—visual processing and ocular-motor responses

Human interaction with the external world involves the utilization of a fully integrated sensory system. To deal and interact with the external world, our system is equipped with microphones for hearing and video cameras for seeing (two eyes for stereo vision processing; two cameras per eye—foveal and peripheral camera—to mimic foveated vision of biological systems). The peripheral cameras provide a wide visual view of the environment, whereas the foveal cameras provide a more detailed view of a smaller portion of the world.

Results from neuroscience research show that visual information is transferred along a number of pathways (e.g., magnocellular pathway, parvocellular-blob pathway and parvocellular-interblob pathway) and that visual processes are executed in well-defined areas of the brain. Visual perception results from interconnections between these partly separate and functionally specialized systems. Such a processing system is much too complex to be implemented on-board. The distributed architecture described in Section 2.4 was designed to allow remote execution of such processing models. It allows us to organise vision processing in a brain-like manner, i.e., serially, parallelly with feedforward connections as well as feedback connections, forming networks of interconnecting processing elements.

As a first example that tests the proposed distributed architecture we developed a visual attention system for CB based on the biologically motivated model described in Ref. [32]. This visual attention model exhibits a distributed processing architecture, which is quite typical for the processing of information in the brain. The original visual stream is subdivided into several processing streams associated with different features (color, intensity, orientation, motion and disparity were used) that are in part independent of each other. Further down the processing stream the results must be integrated and synchronized to produce a global saliency map suitable for the selection of the focus of attention. Once the focus of attention is selected, a feedback connection is needed to suppress visual processing during the saccade. The developed architecture allowed us to distribute visual attention processing among eight PC workstations, and provided us with the means to realize the feedforward and feedback connections. One issue that became noticeable when implementing the attention system was that the processing time, and consequently the latency and frame rate, can vary across the visual streams. This led us to develop and test a number of synchronization schemes that enable time synchronization of visual streams running at various frequencies and latencies [23]. The result of the visual attention system is shown in Fig. 9.

We also experimented with ocular-motor responses similar to that of humans. The following biological ocular-motor control schemes have been incorporated into our system:

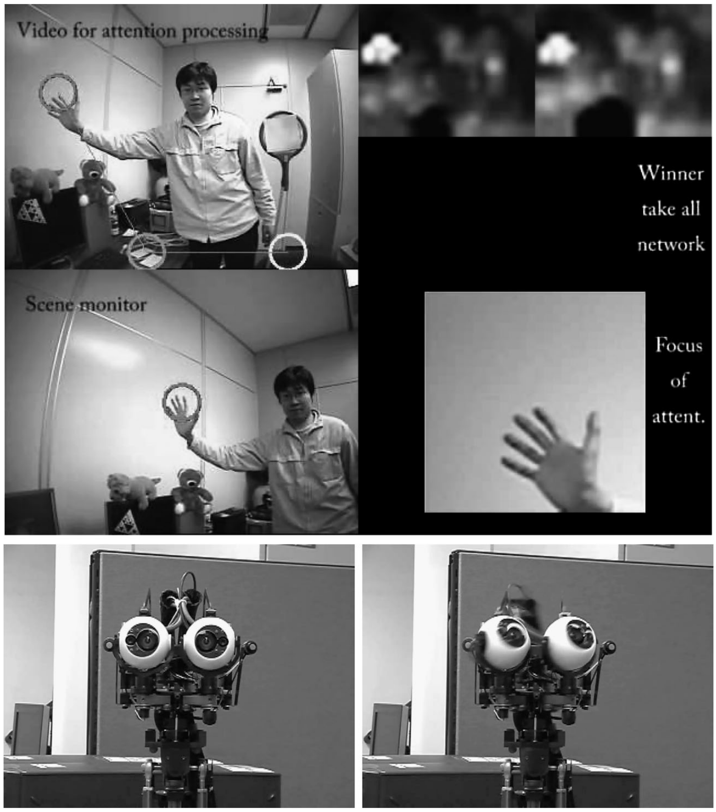

Figure 9. Visual attention—the robot actively saccades to visually acute movement.

- Vergence—minimizing target disparity by symmetric eye movement.
- Saccadic eye motion—quick knee-jerk-type eye movements to redirect gaze.
- Vestibulo-ocular reflex—gaze stabilization by compensating for externally induced head movements (as shown in Fig. 10).
- Coupling of eye movements with head movement.
- Saccade followed by smooth pursuit of a target in an integrated control environment.

These motions form the basis for the realization of active higher-level visual processes.

4. CONCLUSIONS

This paper presented a new integrated humanoid robotic system, CB, developed for the studies of human-like information processing in dealing with the real world. The hardware and software architecture of the overall system were presented. Three aspects of our system were discussed: (i) it provides sufficient power for

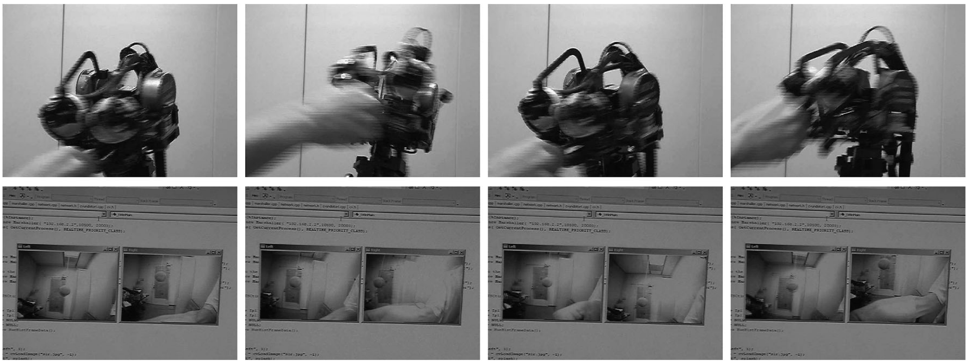

Figure 10. Vestibulo-ocular reflex—sudden head movements while CB fixated on a target (a tennis ball); in this experiment, stability control was applied to the left eye only.

walking, (ii) it has force controllability and (iii) it has a fully supported perceptual system, with a distributed architecture to emulate brain-like processing of sensory information.

The humanoid robot CB, we believe, is the first humanoid robotic system that is capable of full-body force-based (compliant) control. It has a similar range of motion, with a similar configuration (50 d.o.f.) and similar performance as a human. Additionally, its perceptual system attempts to mimic that of humans. These characteristics makes CB suitable as a research tool to investigate the neuroscience of information processing in the brain. This is because, we believe, a sophisticated system such as CB will impose the appropriate constraints by placing our exploration within the context of human interactions within human environments.

With our current human-like system, our immediate objectives are to conduct the following studies:

- To understand agile and natural human-like movements; in particular, to investigate what are the significant properties necessary to produce natural-looking agile and robust locomotion?
- To understand the role that active interactions play in object learning, e.g., utilizing the human-like perceptual system, an object reaching and grasping system will be developed to manipulate an object and vary the views while learning the necessary features required to represent the object.

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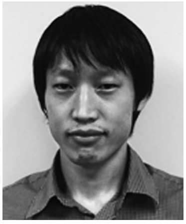

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