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Stories of QRIO and PINO, and Beyond: Lessons Learned from Small Humanoid Projects From R&D to Business

Masahiro Fujita*, Yasunori Kawanami†, Kiyokazu Miyazawa‡
and Masaya Kinoshita§

AI Technology Division, Technology Infrastructure Center,
Sony Group Corporation, 2-10-1, Osaki,
Shinagawa, Tokyo, Japan
**Masahiro.fujita@sony.com*
†Yasunori.kawanami@sony.com
‡Kiyokazu.Miyazawa@sony.com
§Masaya.A.Kinoshita@sony.com

Kunihito Sawai

Creative Center, Creative Platform,
Sony Group Corporation,
1-7-1, Konan, Minato-ku, Tokyo, Japan
Kunihito.Sawai@sony.com

Fuminori Yamasaki

iXs Co., Ltd., 7-7, Shin-Kawasaki, Saiwai,
Kawasaki, Kanagawa, Japan
yamasaki@ixs.co.jp

Tatsuya Matsui

Flower Robotics Inc., J-House 301, Minami Aoyama,
Shibuya, Tokyo 150, Japan
matsui@flower-robotics.com

Ken Endo

Sony Computer Science Laboratories, Inc., 3-14-13,
Higashigotanda, Shinagawa, Tokyo, Japan
XiBorg Inc., 402, 6-34-3, Jingumae, Shibuya, Tokyo, Japan
ken.f.endo@sony.com

*Corresponding author.

Shu Ishiguro
Future Robotics Technology Center, Chiba Institute of Technology, 2-17-1, Tsudanuma, Narashino, Chiba 275-0016 Japan
shu_i@mvi.biglobe.ne.jp

Hiroaki Kitano
Sony Group Corporation, 1-7-1, Konan, Minato-ku, Tokyo, Japan
Sony Computer Science Laboratories, Inc., 3-14-13, Higashigotanda, Shinagawa, Tokyo, Japan
Okinawa Institute of Science and Technology Graduate School, 1919-1, Tancha, Onna-Son, Kunigami-gun, Okinawa 904-0495, Japan
Hiroaki.kitano@sony.com

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In 1997, Sony announced AIBO, a fully autonomous small quadruped robot for home entertainment, and in 1999 the company began selling it as a consumer product. Soon after development, two small humanoid robots were announced. One was QRIO by Sony, which is about 60 cm height body with dynamical bipedal walking and whole-body cooperative control. The other was PINO by the ERATO Kitano Symbiotic Systems Project, which is about 70 cm height body, Open HW/SW with inexpensive off-the-shelf component. In this paper, we revisit the two humanoids and nearly 20-year-old technologies, and discuss what were done 20 years ago, what have been achieved and what challenges are ahead.

Keywords: QRIO; PINO; zero moment point; whole-body motion control; force control; series-elastic actuator; genetic algorithm; behavior control architecture; cognitive developmental robotics; OPEN-R; OpenPINO; Digital-Twin; prosthesis; intelligence dynamics; multi-modal large language model.

1. Introduction

In 1997, Sony announced that it had developed a small four-legged robot, dog-like for home entertainment.[1,2] Around the same time, Honda P2[3] was disclosed and had significant impact on the humanoid research community. In 1999, the small four-legged robot called AIBO was placed on the market as the world's first consumer robot product.[1] Around the time when sale of AIBO began, two small humanoid robots were announced. One of the two was QRIO[4] by Sony which is about a height of 60 cm, and the other was PINO[5,6] developed by the Exploratory Research for Advanced Technology (ERATO) Kitano Symbiotic Systems Project which is about a height of 70 cm as shown in Fig. 1.

Both small humanoids had different objectives at that moment in humanoids. QRIO aimed at entertainment at home, but PINO aimed at an in-expensive humanoid robot platform. However, both had a common objective, which was to challenge commercialization of humanoid robots in consumer market. It was clear

(a) QRIO (SDR-4X)

(b) PINO

Fig. 1. QRIO and PINO.

that neither small humanoid was intended for physical labor or manual labor. QRIO's target was to entertain consumers by providing dynamic dancing, singing, and interacting with a spoken language, which expanded AIBO's direction. PINO's target was to explore applications of humanoids by many researchers and entrepreneurs through an open technology platform with inexpensive off-the-shelf components.

Interestingly, both activities had adopted an open strategy. QRIO used OPEN-R,[2] which was proposed and used in AIBO. OPEN-R aimed at modularization of hardware and software and defined the communication protocols between the modules. Especially software protocol in OPEN-R was a message passing-type one, which is almost the same as ROS-1 and ROS-2.[7] In addition, OPEN-R coped with "Style Flexibility"[8] of various configurations of robots. PINO opened all technology information as OpenPINO.[6] It aimed at inexpensive humanoid platform; therefore, the hardware modules are inexpensive off-the-shelf parts, and the protocols were the existing standard ones.

Both humanoid robots were designed with special attentions to visual aesthetic with personas behind the design, which was not prioritized for humanoids before QRIO and PINO. Our challenge in the design of humanoids was to fulfill the requirements of both appearances to draw the attention of consumers and functionality of dynamic motions. In addition, their nature as consumer products meant that safety was the most important requirement. The main reason why both humanoids were about 60–70 cm in height, weighted about 4.5–6.5 kg and had a round shape, was to maintain safety when the humanoids physically interact with humans and the environment.

Another feature of QRIO and PINO activities was to foster technology skills and business acumen of researchers, engineers, and planners of artificial intelligence (AI) and robotics. Through the projects, the researchers and engineers were trained well and gained experience with AI and robotics, enabling them to utilize the technologies developed in the projects for different targets. In fact, there are several spin-off companies from PINO project utilizing the experience and technologies developed in PINO. From QRIO, there are many advanced AI and robotics technologies and prototypes developed.

In this paper, we would like to review both QRIO and PINO, and discuss the technological progress of humanoid robots, or in general AI and robotics from the 2000s to the 2020s. The remainder of this paper will be organized as follows. First, we will briefly go over the short stories of QRIO and PINO as an overview as what the humanoids were. Then, we will touch upon the technology trends of humanoid in the context of QRIO and PINO, and Post-QRIO/PINO activities. After that, we provide details which describe QRIO and Post-QRIO, followed by PINO and Post-PINO activities. In the final section, we discuss what were achieved in the 2000s, and the 2020s, and what challenges remain for humanoid robots.

2. Short Stories of QRIO and PINO

2.1. *Short story of QRIO and post-QRIO*

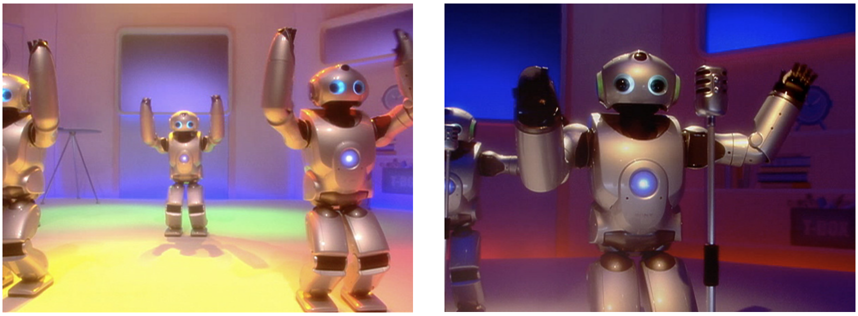
2.1.1. *QRIO*

QRIO was developed as a consumer product for entertainment, like AIBO. Compared with AIBO, QRIO had significant abilities of dynamic motion including whole-body dancing and entertainment through spoken dialogue using many intelligent functions. The key concept consisted of two elements, which were "motion entertainment" and "communication & interaction entertainment".

To reduce the cost, QRIO utilized AIBO's components and technologies such as main processor board with a dedicated LSI for color detection and serial bus controller (OPEN-R bus). An operating system (OS, Aperios) and a module software framework called OPEN-R,[2] which used both synchronized and unsynchronized message passing with shallow memory copy and deep memory copy were used if necessary to reduce the message copy cost. ROS-1 and ROS-2[7] deployed a similar mechanism.

In addition to utilizing AIBO's components and technologies, we developed and implemented more advanced technologies for QRIO.[9] In terms of dedicated devices for QRIO, Intelligent Servo-Actuator (ISA) with small but strong torque generation, a dedicated stereo vision processor, and a carefully designed mechanical structure for safety as well as for recovery from any postures are used.

Using those advanced mechatronics, devices, and sensors, we achieved dynamical biped walking control, whole-body-controlled dancing, and intelligent responses, behaviors and spoken dialogue with intelligent functions such as computer vision



(a) Dancing performance (b) Sing a song with harmony

Fig. 2. Dancing performance and singing performance.

(CV) for face detection/identification, simultaneous localization and mapping (SLAM), auditory scene analysis for sound source direction estimation, speech recognition/speaker identification, phoneme sequence acquisition, speech synthesis and singing voice synthesis, natural language processing,[10] and so on.

Autonomous Behavior Architecture was developed to integrate and properly coordinate those intelligent functions, so that QRIO could be a fully autonomous humanoid that can follow user's voice commands as well as spontaneously generate the proper behaviors.[4,10] QRIO was an entertainer to show dynamic dancing, singing a song with harmony, and spoken dialogue partner with those advanced technologies as shown in Fig. 2.

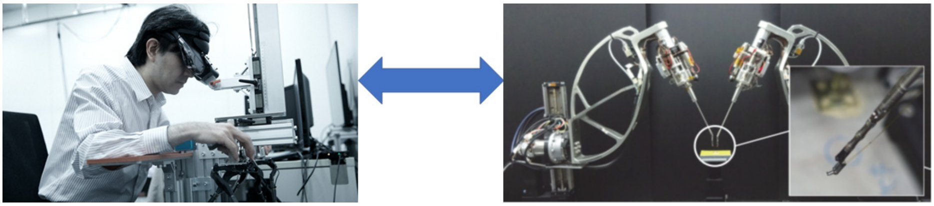
2.1.2. *Post-QRIO*

After the QRIO project was finished, we had a few directions, which were (i) intelligent CE products through intelligent functions developed in AIBO/QRIO, (ii) Intelligence Dynamics (ID) for open-ended growing robot agent,[11,12] and (iii) super-human performance robots.[13]

As examples of the first direction, face detection and smile detection in captured image were used for a digital camera's features such as auto-focus on detected face, and auto-shutter when a face is having a smile.

The second direction was to achieve developmental intelligence in a self-supervised fashion with a predictive function. We named it "ID".[11,12] The challenge was for agents like AIBO and QRIO to grow continuously as open-ended system, which was crucial for the agents not to be boring to users. Details will be given in Sec. 7.

The third direction was to achieve a robot that can perform physical tasks that human cannot do. Examples include a super-precise and force-sensitive bilateral robot system for medical purposes such as brain surgery [Fig. 3(a)], and a legged robot named Tachyon[14,15] that can traverse with a high payload over complex terrain such as stairs [Fig. 3(b)]. In those applications, force control technologies were crucial. We developed novel devices in order to achieve such robots in the real world.



(a) Super precision, super force-sensitive bilateral robot system

(b) Tachyon climbing stairs with heavy payload

(c) Elderly care robot with intimate design and interaction

Fig. 3. Post-QRIO activities. (a) Super-precise and super-force-sensitive bilateral robot system, (b) Tachyon climbing stairs with heavy payload (20 kg), and (c) elderly care robot, HANAMOFLOR.

A Fiber-Bragg-Grating (FBG)-based super-sensitive force sensor was developed for a super-precise and force-sensitive bilateral robot system.[13] A torque control actuator called a "Virtualized Actuator (VA)[16]" and "compact Series–Parallel-Elastic-Actuator (SPEA)[14]", with the novel control algorithms such as "Generalized Inverse Dynamics (GID)[16]" and "Multi-Contact Dynamics Controller and Stabilizer (MCDS)[17]" were developed for physical interactive robots. Details will be given in Sec. 6. In addition, an elderly care robot used in care-house is developed, whose focus is to interact with elderlies without fear, but with intimacy to activate communication [Fig. 3(c)]. It helps caregivers in facilities, and external design is an important factor.

These three directions of "intelligent CE products", "ID[11,12]" and "super performance with force control" have been studied and have contributed to technologies and industries.

2.2. *Short story of PINO and post-PINO*

2.2.1. *PINO*

PINO[5,6] was developed with the aim to provide opportunities for many researchers to study humanoid technologies, and for many entrepreneurs to explore applications and commercialization of humanoids. Therefore, it needs to be inexpensive and open-sourced, so that it would be easy for people to purchase it to build PINO, and to develop technologies and explore the applications. Therefore, PINO used inexpensive off-the-shelf hardware parts to meet those requirements. All technology information was disclosed as OpenPINO under a GNU General Public License. The concept of PINO was "Poor-man's humanoid".

Technology development in the PINO project focused on walking control.[5,6] Because of inexpensive parts without high precision performance, the typical Zero Moment Point (ZMP) control was difficult to implement for PINO. Therefore, non-programing without explicit ZMP computation approach with Genetic Algorithm (GA) approaches was taken for gait pattern generation.[18] Moreover, co-evolution of hardware and walking controller was studied to explore suitable lengths of legs with control parameters with GA.[19]

Another significant feature of the PINO project was the deep consideration of aesthetic design to draw the attention of consumer, which was not addressed in the design of other humanoid.[6] In reality, after PINO was released, it garnered much attention from public, and was signified by its presence in prestigious museum such as La Biennale de Venezia and Museum of the Modern Art, New York (Fig. 4).

A company called ZMP Inc. was created for the market development and further improvement of the technologies. Three aspects of PINO had been brought to the market, namely, (i) PINO as a humanoid platform for research, (ii) business related to components with a standard interface for robots and other applications, and (iii) image licensing business.

The aim of the first was to sell the robot platform to universities and companies for research and education purposes. The second was to sell component and supplies, consisting of mechanical frames, CPU modules, motors, gear heads, and batteries. Furthermore, some modules using those components with a standard definition of electronics, bus protocol, and mechanical interface, were also sold to expand applications beyond PINO. The third aim was to license PINO's image IP for a character in a promotional music video (Hikaru Utada at Toshiba EMI), and in TV

(a) La Biennale de Venezia (b) Museum of Modern Art New York (MoMA)

Fig. 4. PINO at prestigious museum.

(a) Toy robot of PINO (b) Picture book

Fig. 5. Image license business examples.

commercials (UCC Coffee Corp. and NTT DoCoMo Kyushu), robot toys of PINO (Tsukuda Original Corp.), and a picture book featuring PINO (Fig. 5).

2.2.2. *Post-PINO*

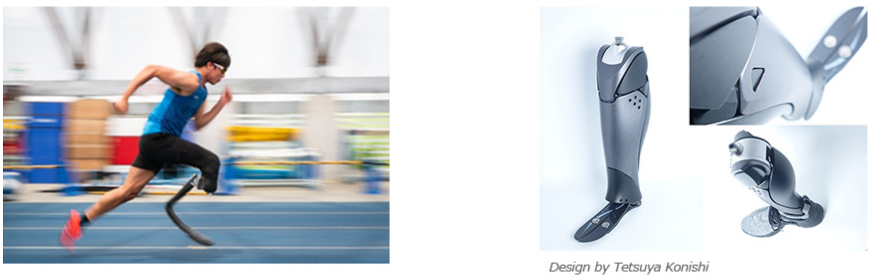
Post-PINO activities were characterized as business explorations of robotics. In this paper, we introduce four startup companies.

The first company is ZMP Inc.,[20] which was established in 2001 to create business from PINO project achievements. ZMP developed PINO-II, which was an improved version of PINO. ZMP expanded its activities to autonomous car, logistics support robotics, and robot cloud management system.

The second company is Flower Robotics Inc.,[21] which was engaged in the exterior design of PINO. The company commercialized human-form robots such as a flower girl at an event and a mannequin-type robot for display as shown in Fig. 6(a), which utilizes its design policy, and continues doing so today. The story of PINO's design will be described in Sec. 3.2.

The third company is XiBorg Inc.,[22] funded with the aim of updating the definition of the human body with technology. Humanoid development needs to pay attention not only to the human-like shape, but also to the human body function. For example, if we can not only compensate for impaired functions, but also expand them, we can break the boundaries between physical functions for people with disabilities, able-bodied people, and the elderly, and change the negative perception of lack of physical ability. To do so, we need to solve not only technical problems but also social problems. Regarding technical problems, it is necessary to unravel the human nervous system, reflex system, musculoskeletal system, and brain of the body, and design technology that takes physical movement into account. Regarding social

(a) Flower girl robot Posy and mannequin-type robot by Flower Robotics



(b) Prosthetic leg fro athletes (left) and Powered-Knee Prosthesis by XiBorg

Fig. 6. Post-PINO activities by spin-off companies.

problems (e.g., delivery of technology to people with disabilities in developing regions), we need to consider both geographical issues and social issues that encompass cultural, economic, religious, and environmental issues.

One of the complete examples is the support of athletes in track and field with the prosthetic leg XiBorg developed as shown in Fig. 6(b). The ultimate goal is to become the fastest human being faster than an ordinary athlete. Options such as the weight and hardness of the prosthetic leg that even able-bodied world record holders cannot make can be fitted according to the physical ability of the prosthetic leg wearer.

Another example is to utilize Powered-Knee-Prosthesis with Series-Elastic-Actuator (PAP-SEA).[23] Note that SEA has already been mentioned for its usefulness for legged robot (Tachyon) for super-mobility onto wild terrain with heavy payload in Secs. 2.1.2 and 6.2. The details are described in Sec. 9.1.

The fourth company is iXs Co., Ltd.,[24] whose business is to focus not only on automation through robotics but on the entire workflow of Infrastructure inspection and management tasks. Automated tasks performed by robots are of course important. However, we need to be conscious of people using robots, the environment for robots, training people how to use robots, and the ease and cost of maintenance of robots. An example of such business is inspections of infrastructure maintenance and management, in which it is important to consider not only the functions of robots, but also reducing the total cost including data collection, data management, data analysis, and report generation. iXs has developed the Digital-Twin with their robotics technologies called i-Con Walker and has achieved efficiency and cost reduction considering the entire workflow described above. The details will be described in Sec. 9.2.

3. Design Consciousness

As we have emphasized, QRIO and PINO were both designed with consideration given to the exterior and humanoid functions, which was a novel and unique approach compared to the existing humanoids in the 2000s. This section gives brief summaries of QRIO and PINO design philosophy.[6,25]

3.1. *Design story of QRIO*

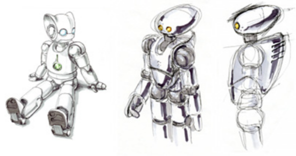
The most important message point of QRIO was "to achieve romance between technology and consumers". Therefore, a designer of QRIO had to understand what kinds of cutting-edge technology were achieved with QRIO.

Fortunately, we had developed AIBO as a consumer product with many cutting-edge AI technologies, and SDR-3X as a dynamic dancing humanoid robot with cutting-edge control technologies. The designer of QRIO[25] knew those conditions and constraints. Character image was the most important part, and after many trials using rough sketches as shown in Fig. 7. The design points of QRIO were, (i) outstanding eyes with color light-emitting diodes (LEDs) for emotional expressions, (ii) chest button with a blinking LED to express sense of life, (iii) alien-like head shape with gentle atmosphere, (iv) sphere shape joint for gentle impression, (v) handle for easy carrying while fitting and blending into a part of body naturally, and (vi) no-gap joints to avoid pinching. The lengths of arms, legs, and body were determined in consideration of biped walking, dynamic dancing, recover from falling, etc., which were for QRIO's entertainment features.

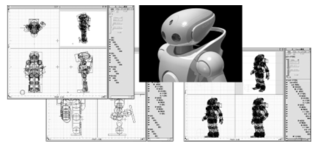
Note that the design process of QRIO was iterative between exterior designer and robot engineers. Figure 7 shows the rough design process of QRIO, but it was not a water-fall process. One of the significant points was to use clay mockup with movable joints with the constraints of similar to real joints. It covered three-dimensional (3D) CG software to show the reality of postures. Figure 7(f) shows some messages from the designer to QRIO engineers to explain the important points of design. Many interactions and discussions were held to achieve a high-quality dynamics and an appealing design.

3.2. *Design story of PINO*

One of the salient features of PINO is its exterior design.[6] We consider the aesthetic design of robots to be a critically important factor for acceptance by the public.

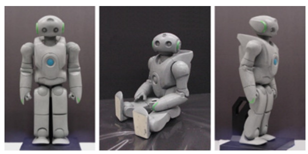


(a) Some design examples at beginning

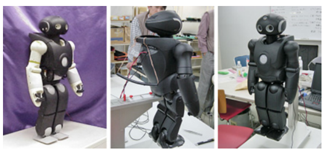


(b) Verification on CG SW (Shade) with possible Operating joint angles

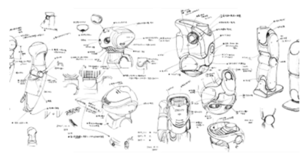
(c) Cray Mockup with movable joints



(d) Cray Mockyp for the 1st prototype



(e) The 1st prototype of QRIO



(f) Design point memos to QRID engineers for the 2nd prototype.

Fig. 7. Design story of QRIO.

While traditional robots directly expose the mechanisms inside, this does not appeal to the general public. Our interest in robotics research includes the issue of how the general public react to humanoids and what designs are more acceptable. Thus, we built a humanoid with an exterior that we consider to be acceptable and observed how people react (Fig. 8).

As for form, it was deemed necessary to design its proportions as recognizably human as possible; deviating too far from the instantly recognizable form of a human child could cause it to be seen as an altogether different object. From a psychological point of view, we noted that even the casual observer focuses more attentively and ultimately more affectionately upon a similarly structured form.

Before starting the design sketches, we searched for a universal element in the representation of the human form. Images handed down from the archives of such representational forms, we believed, provided the key to integrating into the future what has universally been acknowledged as fundamental beauty. Ancient Greek sculptures and more significantly, as it turned out, the more folkloric marionettes to name a few were evoked, not only for their obvious beauty, but just as importantly for their mournful aspirations towards perfection. The marionette, with its mechanisms to facilitate movement and expression provided the ideal framework by

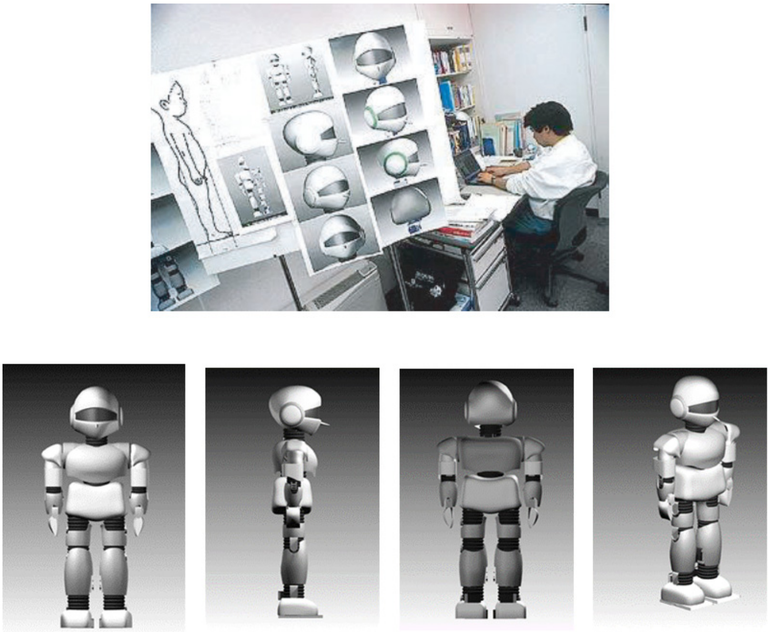


Fig. 8. Design story of PINO.

which PINO could be adapted. "PINOcchio," whose story needs no explanation, seemed an apt metaphor for our search for human qualities within the mechanical structures of our creation. We felt the necessity to place PINO somewhere in time, more specifically within the context of a story to elevate him above the static realm of the object. In his gestation, PINO symbolically expresses not only our desires but also humankind's frail, uncertain steps towards growth and the true meaning of the word "human".

In addition to philosophical considerations, PINO was composed of inexpensive, non-high-precision parts, which meant that walking performance would be not very high. Therefore, the image of PINO was "a one-year-old child with a waddle", which could be accepted by general audiences.

4. Technological Progress Overview

In this section, we provide an overview of technological progresses related to our activities with QRIO and PINO, which were in the 2000s, and Post-QRIO and Post-PINO, which have been in the 2010s and the 2020s.

4.1. *Technology in general in popular consumer products*

First, some technologies have been progressing in general. This means that non-robotics products have been contributing to technological developments. In particular, semiconductor process has been improving according to Moore's law,[26] which is supported by a huge investment in chip development for smartphone and other products.

For example, in terms of AIBO specification as consumer product[2] the processing unit in the 2000s was about a 300 MHz CPU-clock and 16 MB main memory. In 2023, a CPU-clock is about 3 GHz with six cores.[27] Furthermore, it has a GPU, a neural network engine, etc. The main memory is more than 128 GB. Therefore, compared to the 2000s, the CPU alone has improved to a clock that is 10 times faster with six times as many cores, and other extended computations in one chip. The memory size has become about 400 times larger.

Regarding WiFi,[28] the most popular WiFi standard in the 2000s was 802.11b, which is about 11 Mbps. In the 2020s, the popular standard is 802.11 ax with 9.6 Gbps, which is about 100 times. In addition, the cellular infrastructure is now very popular in the world. 5G technology has a speed of about 20 Gbps. Wireless connected robots with WiFi were proposed in the 1990s,[29] but the bandwidth or speed was not sufficient to send sensors and commands information between robot and PCs. However, in the 2020s the performance of communication is almost satisfactory except for latency. So, the functions such as force control need embedded processing even now.

Image sensor technology is also in the category. In the 2000s, there were a few products of image sensing for small humanoid. We developed dedicated sensor for recognition. QRIO's image sensor was 110k pixels.[4,10] However, smartphones in the 2020 were commonly equipped with image sensor, and moreover depth sensor. The image sensor has about 50M pixels, which is about 50 times better than in the 2000s.

4.2. *Technologies speciffc for physically moving robots*

However, we should note here that there are devices that need more improvement in performance. For example, batteries and actuators are such devices.

Batteries have been improved thanks to smartphones. However, physically moving objects need more power than smartphones. Electric Vehicles (EVs) are now in the consumer market, and getting better, but the state-of-the art battery product is not sufficient for long-distance driving. It is said that the lithium-ion battery technology becomes the performance limitation. From AIBO to Tachyon, the W h/L of the cell improved by about 1.5 times. However, package technologies are improved in safety function, intelligent charge function, etc.

An actuator is another example from this category. In this paper, we will describe our efforts with actuators called the ISA for QRIO and the VA for force control robot systems. We integrated not only simple actuation function but also force sensors, feedback control, and gears in small housing of the motors. Details will be described in Secs. 5 and 6.

Recently, the SEA has become popular in legged robots, which is essentially elastic with spring and dumping factors, so it is robust against collision impact and safe for physical contact with human and the environment. We used SEA in Tachyon to achieve compliant legs. Note that the SEA technology is used for PKP as well. The details are described in Secs. 6.2 and 9.1.

4.3. *Intelligent functions for physically moving robots*

Humanoid or robotics in general has been a technology driver for some intelligent functions.

SLAM is one such technology. In the 2000s, QRIO achieved SLAM technology with its stereo vision system. It can build and memorize 2.5-dimensional map.[30] Details will be described in Sec. 5.4.1. In the 2020s, with the spread of 3D sensors such as for smartphones, drones, and EVs, SLAM has become stabler and easier to use.

CV and Automatic Speech Recognition (ASR) were used in QRIO and PINO in the 2000s. However, performance was not enough to communicate with a user's voice in a home environment because of the far field effect and noise. Thanks to Deep Neural Network (DNN) technology in the middle of the 2010s, performance was drastically improved and based on some benchmarks it overperforms human.[31] Thanks to the progress of CPU system and wireless communication system, the edge–cloud collaboration system has become popular. Therefore, tele-operated robots with CV and ASR have been widely proposed both in industry and academia.

The significant progress of Machine Learning in the 2020s is the Foundation Model[32] or the Large Language Model (LLM)[33] with self-supervised learning.[33] As described later we had proposed ID[11,12] in about 2010. It was self-supervised learning with predictive function. At that time, DNN was not yet known, and we used typical Machine Learning such as Recurrent Neural Networks (RNNs). The Transformer[33] had a significant impact on self-supervised learning using huge internet text data as training without labeling. The technology is now used for planners and skill learners for robotics. Further discussions are in Secs. 10.3 and 10.4.

Accordingly, physical interaction or manipulation technology is one of the main targets in the 2020s. It was difficult for QRIO and PINO to physically interact with humans and objects because safety was the most important issues, as they were consumer products despite their small size. Force control for feet was implemented for biped walking. However, physical interaction with a human or manipulation with force control was still challenging in the 2000s. As we describe above, force-controlled actuator technologies such as VA[9,16,17,34] and MCDS for whole-body control were proposed in about the 2010s. However, manipulating objects with varieties of physical properties, and visual properties are still challenging in the 2020s.

5. QRIO for Home Entertainment

As we introduced QRIO in Sec. 2.1, QRIO as a home entertainment humanoid robot had to have some features and technologies to achieve them. In this section, we describe the functions and technologies that achieved the features of QRIO, which

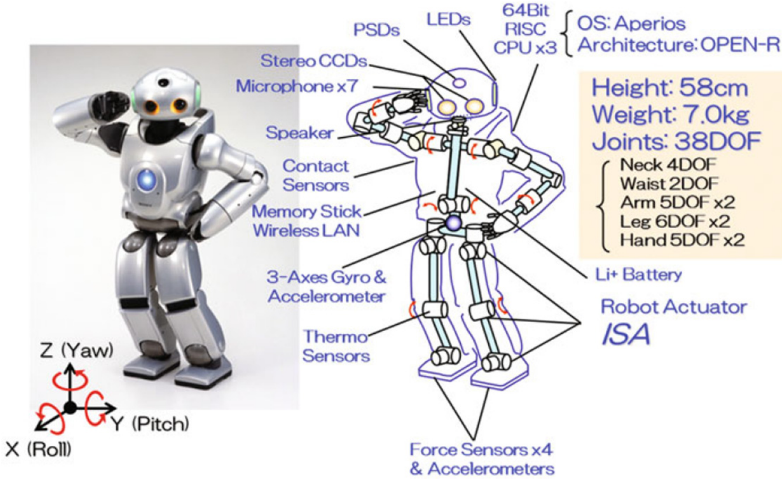
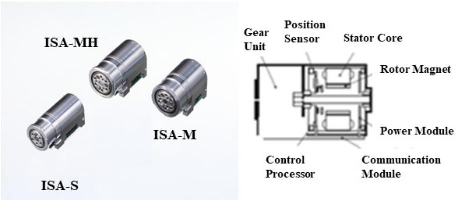


Fig. 9. Configuration of QRIO.

were "motion entertainment" and "communication/interaction entertainment". The details are described in Refs. 9 and 10.

5.1. *Hardware of QRIO*

QRIO's major hardware configuration is shown in Fig. 9. QRIO's height is 58 cm, and it weighs about 7.0 kg. It has 38 degrees of freedom (DOF) in total. Each leg has six DOF, the waist has two DOF, each arm has five DOF, the neck has four DOF, and each hand has five independent fingers. Major joints in legs, arms, and the waist are actuated by ISA shown in Fig. 10. ISA is an actuator that includes a motor, a reduction gear, a motor driver, a control processor, a position sensor, and a serial communication interface in one module and is designed to meet high power/weight ratio, wide bandwidth, high efficiency, and high back drivability. For motion control, gyroscopic sensors and accelerometers are mounted on the pelvis. Each sole has four force sensors and one accelerometer in it. Contact sensors and temperature sensors are distributed on appropriate parts mainly for safety use.



(a) Intelligent Servo Actuator (ISA)

Type	ISA-S	ISA-M	ISA-MH
Rated torque [Nm]	0.6	1.4	2.2
Size (diameter × length) [mm]	25×54.5	32×52.5	32×57.5
Weight [g]	84	123	157

(b) Specification of Intelligent Servo Actuator (ISA)

Fig. 10. ISA.

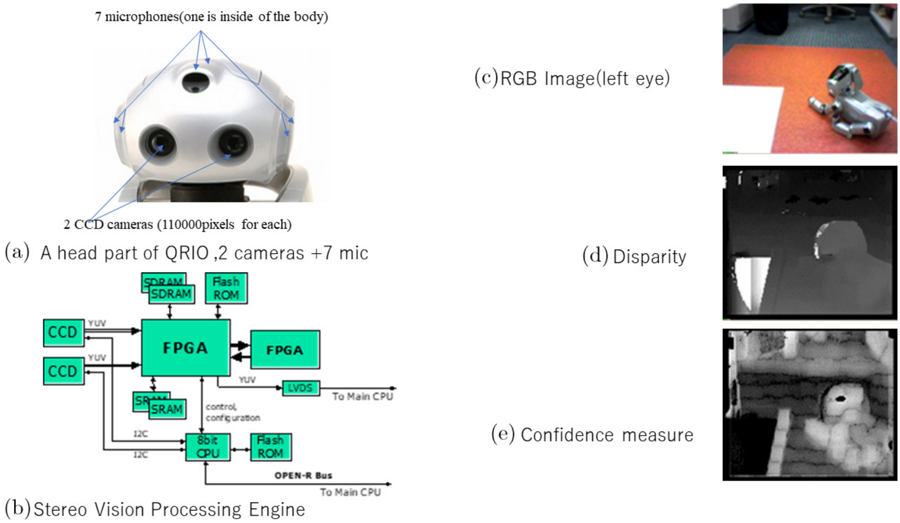
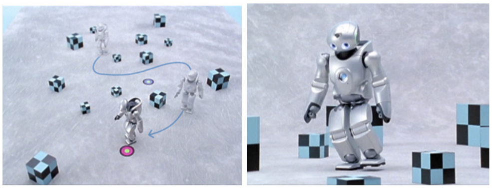


Fig. 11. The part of QRIO's head for audio and vision sensing.

To achieve real-time and real-world space perception, a micro-stereo vision system is mounted in the head. It comprises two small color charge-coupled device (CCD) cameras with about 110 k pixels whose baseline is 50 mm and FPGAs (Fig. 11) to compute the disparity image. An infrared position sensing device (PSD) is also implemented in the head and each hand. Seven microphones are located inside the head to detect a sound source and to recognize an individual speaking. A speaker in the head and LEDs in its eyes, ears, and torso are used to communicate with users and to express QRIO's internal state. QRIO is controlled by three 64-bit RISC processors for motion control, speech recognition and synthesis, and vision and autonomous behavior control. Actuators and most sensors communicate with them via OPEN-R BUS, a serial communication bus used in OPEN-R architecture.[2] All the power is supplied by a lithium-ion battery that enables QRIO to operate for more than 1 h per charge.

5.2. *Motion control system*

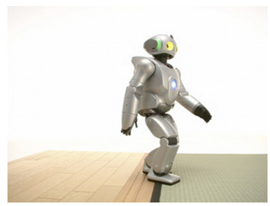
QRIO's motion control system called "real-time integrated adaptive motion control system" was developed to cope with a variety of situations occurring in home use. It has to not only perform motion patterns created off-line, but also generate gait patterns in real-time according to the surrounding environment [Figs. 12(a) and 12(b)], and stabilize them even if there are uneven terrains [Fig. 12(d)] and unknown disturbances such as external forces [Fig. 12(e)]. It also has to engage in protective motion when it falls over or something is pinched in the joints [Figs. 13(a) and 13(b)]. If it is picked up, it must stop all motion safely and should restart the control when it is put on the floor again [Fig. 13(c)]. To meet these requirements,



(a) Real-time walking direction control

(b) Transition control of walking, running, and jumping

(c) Natural gait control by line contact walking



(d) Terrain adaptation motion control

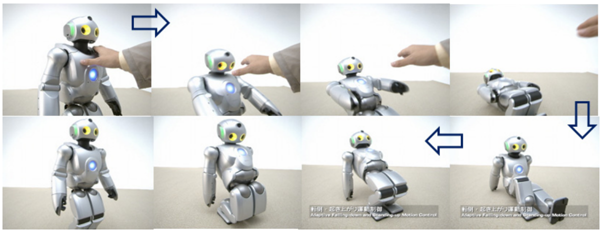
(e) External force control

Fig. 12. The requirements for home environment.

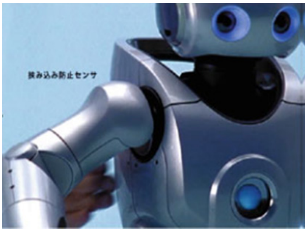
real-time integrated adaptive motion control system was developed. Details are described in Refs. 4, 9, and 10.

In short, the real-time whole-body stabilizing motion control generates gait patterns and coordinates them with upper body motion while modifying a part of the whole-body motion to make it dynamically stable, which includes a ZMP equation solver in the real time. QRIO's ZMP equation solver can cope with flight phases to achieve integrated motion control of walking, jumping, and running and transition among them as shown in Fig. 12(b) as well as motion control with point and line contact between soles and ground, which enables natural gait control with a wider stride as shown in Fig. 12(c).

External force adaptive motion control estimates perturbations by using IMU and modifies the footprint in subsequent steps to keep balance while maintaining ZMP stability criteria. The step length is modified in both sagittal and lateral planes.



(a) Protective motion and recovering when QRID falls over



(b) Pinch detection and avoidance

(c) Control motion when picking up to move a different place and puting it

Fig. 13. Requirements in interaction cases.

Figure 12(e) shows external force adaptive control to stop when QRIO faces a user or other objects.

5.3. *Motion editor*

The main entertainment feature of QRIO is dancing performance. A motion editing software that can be easily used by creators was developed as shown in Fig. 14.

It has timelines for upper body motion, gait patterns, pelvis motions, and music to design synchronous performance among them. The designed motions are real-time processed by dynamics filter that includes whole-body stabilizing function described

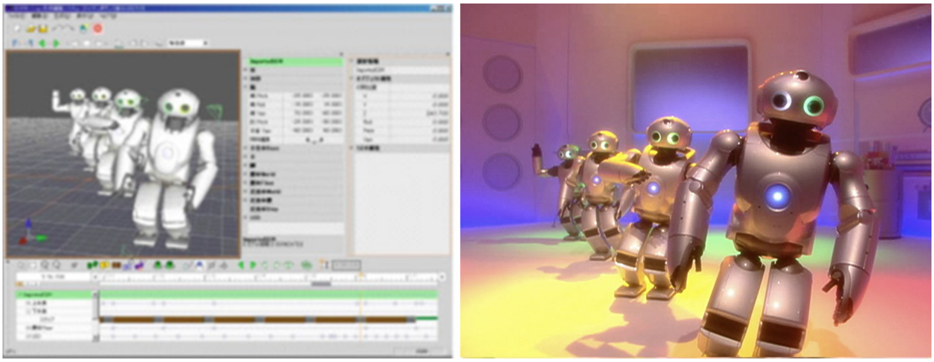
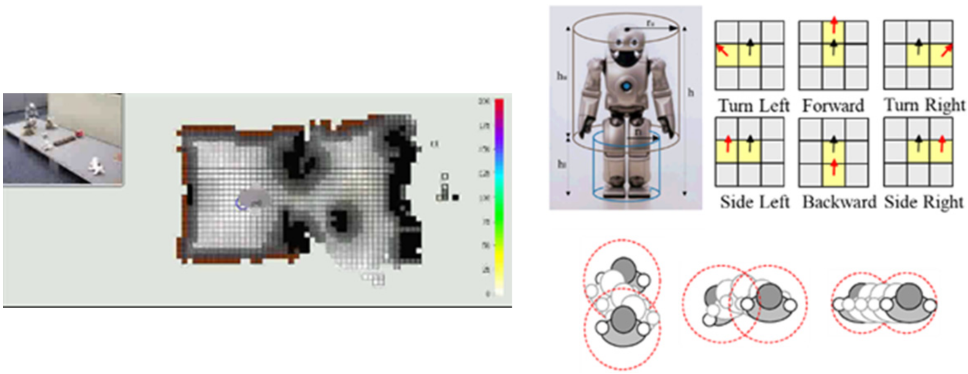


Fig. 14. Motion editor for dancing performance.



(a) 2.5D occupancy map by SLAM with the stereo vision (darker is higher)

(b) QRIO's possible actions and occupied space.

Fig. 15. SLAM and path planning considering multiple motion strategies.

above to convert to the stabilized motion that are expected to be executed on the real QRIO.

5.4. *Intelligent functions*

QRIO had the intelligent functions to interact and communicate with users in home environment.[4,10,35] Here, we focus on special perception and human interaction, which are (i) SLAM and path planning, (ii) face detection and recognition, and (iii) speech recognition, synthesis.

5.4.1. *SLAM and path planning*

Using depth estimation through the stereo vision, QRIO can build a 2.5-dimensional map with SLAM technology[30] as shown in Fig. 15(a). Then, compute the path plan considering QRIO's capability of multiple motion strategies with its necessary space sizes. Examples of this are straight biped walking for normal space, turning when direction should change, and sideways walking in narrow space as shown in Fig. 15(b). QRIO can crawl with its arms and legs, so it can go under a table if there is enough space.

The SLAM information is memorized into long-term memory (LTM), which keeps the information even when power is turned off and recalls it when the power is turned on.

5.4.2. *Face detection and identification with voice direction estimation*

Using the two CCD cameras and seven microphones, QRIO (Fig. 11) can detect human faces with voice direction estimation. For example, as shown in Fig. 16, if QRIO plays with user1 and a ball, then user2 calls QRIO from its left (out of camera view), QRIO estimates the voice direction and turns to the direction to find the

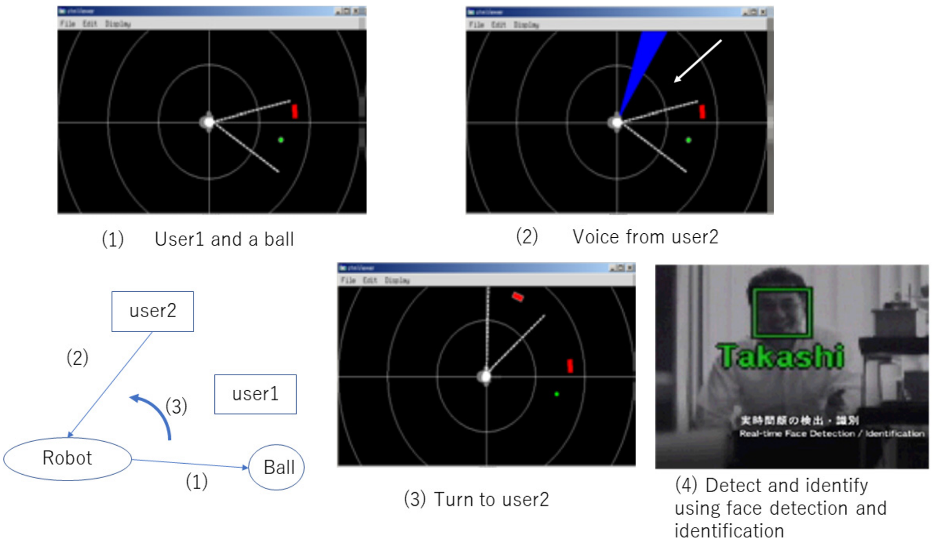


Fig. 16. Face detection and identification with audio–video fusion.

user2. The location of user1 and the ball is memorized on the map of SLAM. Thus, QRIO can memorize the locations of user1, the ball, and user2. We call it short-term memory (STM). We will describe STM later, with face identification functionality and the location information on the map, QRIO can handle multiple persons' interactions.

5.4.3. *Speech recognition and voice synthesis*

Using seven microphones (Fig. 11) QRIO can beamform to enhance a target user's voice to input the speech recognition function through the Hidden Markov Model (HMM). The features of QRIO's speech recognition are (1) small footprint for embedding system (20 k words dictionary), (2) integration of Finite State Automata (FSA) grammar and 3-gram, (3) noise robust acoustic model, and (4) real-time speech recognition. In addition, it is capable of acquiring new words as phoneme sequences. By associating them with the identifiers obtained from face identification or object recognition, it enables QRIO to memorize the names as LTM and to recall the corresponding names when it sees the face or the objects. We will describe LTM later.

As we describe, QRIO can interact with the environment and users using its motions, as well as voice and color LED surrounding its eye. Text-to-speech technology is used to generate QRIO's voice, and the color LED shows its emotional status using the Internal State Model (ISM) described later.

5.5. *Autonomous behavior control architecture*

Because QRIO is designed for use as consumer product and service in home environment, we defined some of the requirements as follows: (i) spontaneous behavior,

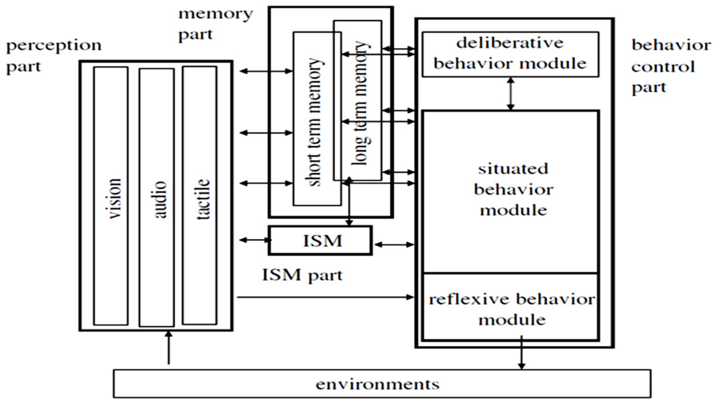


Fig. 17. Autonomous behavior control architecture for QRIO.

(ii) reflexive behavior, situated behavior, and deliberative behavior, (iii) spatial perception with memory, and (iv) dialogue with memory. In order to meet those requirements, we design autonomous behavior control architecture as shown in Fig. 17.

Spontaneous behavior is needed because QRIO is expected to move, dance, and interact with human without any command from a user, which was similar to AIBO.[36] The key idea was to implement the pseudo-instinct-emotion model, or ISM. Considering both the external status such as whether a user is near, or a ball to kick is near, and the internal status of the mode, QRIO releases the selected behavior that is suitable for the situation. The external status is provided by STM and LTM, which are described in Secs. 5.4.2 and 5.4.3.

QRIO has a hybrid of three-layered behavior architecture with reflexive, situated, and deliberative behaviors.[10] The reflexive behavior is important to respond to stimuli very quickly. The motion control functions explained in Sec. 5.2 are in the reflexive behaviors. Turning toward the direction of a user's voice and tracking the target face or object are also implemented in this layer. Situated behaviors are predesigned behaviors for almost all other behaviors such as "kick a ball", "go close to a user", or "show dance performance". Deliberative behaviors are more computational heavy functions such as planning and dialogues. In addition, a user's command is to be executed by strongly biasing one of the situated behaviors. Those behaviors with different computational time are integrated in the hybrid architecture.

Spatial perception with memory or STM and LTM is necessary when QRIO tries to do situated behaviors. For example, when the internal state of QRIO becomes the situation to release "kick a ball", but there is no ball in its camera view, QRIO needs to start "looking for a ball". If there is a ball in QRIO'S spatial memory, QRIO will "go close to a ball" using the STM without searching. It was achieved through integrating SLAM technology, human detection/identification technology, and object detection/identification technology.

Dialogue with a user is very high demand requirement, however; it was still challenging in the 2000s. QRIO focused on dialogue with memory,[35] in which QRIO memorizes some keywords such as the user's favorite foods, music and movies. Those keywords are used for further dialogue to explain the related information but limited for the user to say Yes or No, or a limited sentence to extract further keywords.

5.6. *Emotional grounding symbol and ego architecture*

In this section, more details are described about the situated behavior module and spontaneous behavior mechanism. We call it Emotional Grounding Symbol and EGO architecture.[37]

As shown in Fig. 18, situated behavior module has many behavior modules, and each behavior module is composed of two functions, which are the monitor function and the action function. In the monitor function, the activation level is computed based on the external stimuli and the internal variables. The external stimuli are the messages from aforementioned STM and LTM, and the internal variables are the variables of ISM, which are pseudo-instinct such as "hunger motive (battery status)", "sleep motive (accumulated amount of currents of the actuators)", "interaction motive (the length of time that QRIO doesn't interact with a user)", and "play motive (the length of time that QRIO doesn't interact with objects)". Internal variables are decreasing if there are no related stimuli. So, if the internal variable such as "Play Motive" is under the low boundary of the range, then the monitor functions of the related behavior modules compute high score for activation level, which means the behavior module is valuable to increase the "Play Motive". The monitor functions evaluate its value not only by ISM, but also external stimuli.

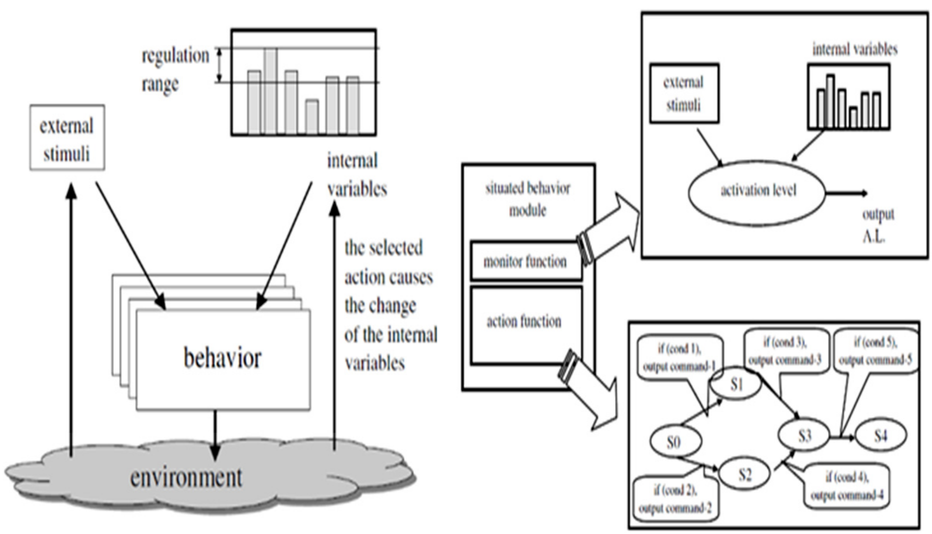


Fig. 18. EGO architecture and situated behavior modules.

If there is a soccer ball, then the activation level becomes high. With the addition of ISM and the external stimuli, the activation level is computed, and compared among the behaviors in situated behavior module. The system selects the behavior that has the highest activation level. Once the behavior is selected, the corresponding action function is executed. The action function is basically implemented by the state machines.

EGO is different from a normal object recognition and behavior assignment of pre-programed action. A symbol of a soccer ball sensed by a camera can be said to be grounding to a "camera sensor" as well as the internal variable of "play motive". Therefore, a soccer ball has semantic meaning to increase the "play motive", and it generates the emotion of "happiness". Thus, it can be called an Emotionally Grounding Symbol and the architecture can be called EGO architecture.[37] We can achieve a system in which a symbol has a semantic meaning not through a dictionary but by naturally assigning a behavior value for the system.

6. Post-QRIO Activities

QRIO was not sold as a product, but; R&D work has been continued using QRIO, and furthermore, advanced technologies have been developed since QRIO's R&D activities in our group. In this paper, we describe two topics; (i) MCDS,[16,17] and (ii) developmental intelligence or ID.[11,12]

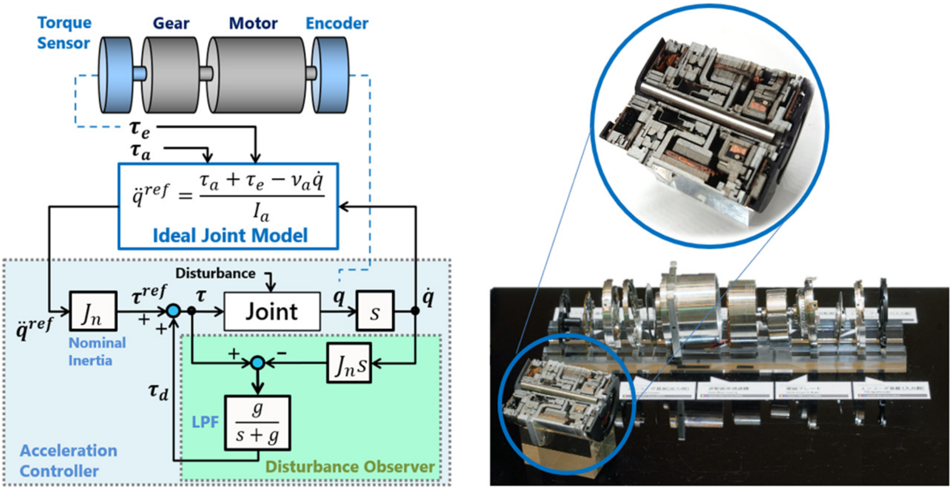
6.1. *Multi-contact dynamics controller and stabilizer*

MCDS is needed when a robot is like a humanoid for moving the body using various parts not only soles but also hands, elbows, and knees, contacting the environment. Advanced force control technology is necessary to achieve it. We developed GID[9,16,17,34] to solve an inverse dynamics problem from a target motion dynamics to get joint forces under various constraints. The Quadratic Programing (QP) solver can use the solutions to achieve the dynamics with many constraints represented by "Equation and Inequation" such as actuators limitations and arm angle limitations.

In order to build a real robot controlled by GID, we developed a VA[16,38] as shown in Fig. 19, with which we can design an actuator with physical parameters such as an inertia moment, a dumping factor, and a friction factor, which we can set as the parameter of the controller inside of VA. Disturbance Observer (DOB) is used in the controller to be stable.

We further developed MCDS,[17] where "Stability" means no-divergence of the momentums of the system. There were some related works when MCDS was proposed[17]; but to our knowledge at that time, MCDS is the only solution to consider the long horizontal contact plan by utilizing a Model Predictive Controller (MPC) and GID.

Figure 20 shows screenshots of spider walk contacting walls by hands and legs to move the body in the upward direction.



(a) Control scheme of VA

(b) Cross-section cut of VA

Fig. 19. VA.

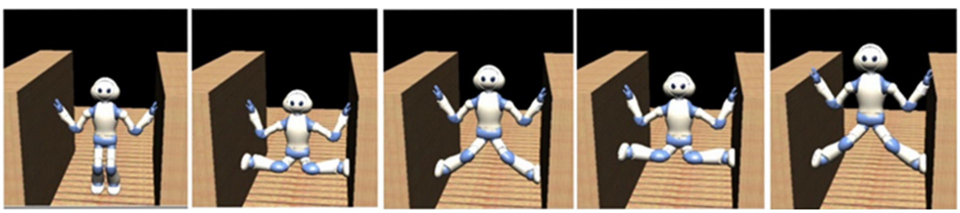
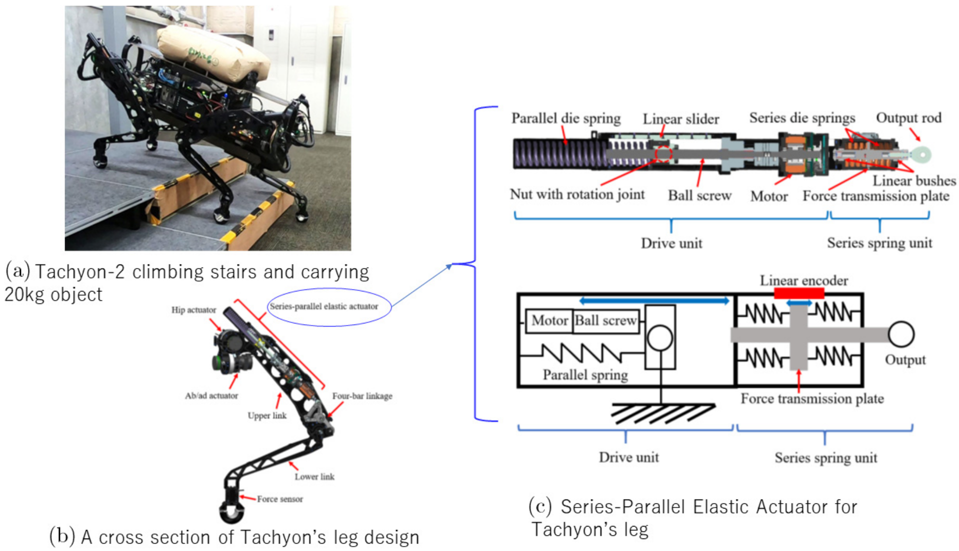


Fig. 20. MCDS and screenshot of spider walk.

6.2. *Four-legged robot Tachyon*

As we described in Sec. 2.1.2, one of Post-QRIO activities has been done to develop legged robot called Tachyon.[14,15] In this section, we describe Tachyon-2,[14] whose features are (i) SPEA[39–41] for high payload legged mobility, (ii) Electric Double Layer Capacitor (EDLC) for impulsive output energy and computer managed motor power controller, and (iii) fast computation algorithm for MCDS with GID. In this paper, we focus on describing (i) SPEA, and (iii) overall control architecture using fast computation algorithm for MCDS with GID. The structure of Tachyon-2's SPEA is shown in Fig. 21. We successfully developed small and light weight SPEA so that Tachyon-2 was the world's first four-legged robot with SPEA. The features of SPEA are to have both a series-spring-dumper for absorbing impulsive collision with environment, and a parallel-spring-dumper for gravity compensation. However, since the inclusion of a spring tends to cause vibration, we have enhanced the stability of Tachyon by controlling the position, including high-frequency force control.



(a) Tachyon-2 climbing stairs and carrying 20kg object

(b) A cross section of Tachyon's leg design

(c) Series-Parallel Elastic Actuator for Tachyon's leg

Fig. 21. Structure of Tachyon-2's leg and SPEA.

Overall motion control software system architecture is shown in Fig. 22. The target velocity, angular velocity, and gait pattern are input from the high-order software, and based on the inputs, the gait scheduler plans each foot to be planted and manages future planted positions and times. The absolute pose estimator calculates the position of the robot's feet, position, and center of gravity from the IMU, encoder, and force sensor. Using the gait scheduler and pose estimator, the center of gravity is stabilized by the center of mass (CoM) stabilizer, and the target center of pressure (CoP) and current swing leg landing point are calculated. To achieve these

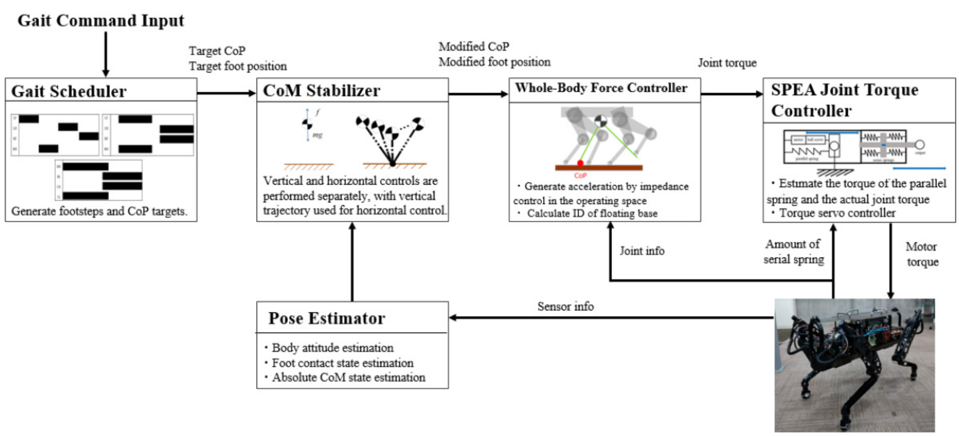


Fig. 22. Overall motion control software system architecture.

targets, the GID calculates the joint torque. The SPEA torque controller is an independent feedback controller used to achieve the desired joint torque; the joint torque other than for the knee is directly input without feedback control. These operations are performed in a real-time loop with 1 ms. Finally, the torque controller inputs torque to the motor of every joint on the robot to achieve low impedance force controllability.

By using the planned CoP and stride length modification as stabilizing inputs, both motion planning and stability are achieved. It is also featured by being able to stabilize the flight phase and being robust against modeling errors. The details of the fast computation algorithm for MCDS with GID are given in Ref. 14.

7. ID Toward Open-Ended System

QRIO was designed as a consumer product with entertainment contents such as dancing with music, and entertainment dialogue, and one of the critical issues at that moment was, how to achieve "intelligent interactions at a human like level". The methods explained in the previous section cannot reach the level of human-like interaction. As a result, they fall short of achieving the goal of entertainment.

Therefore, we took on the challenge of achieving an open-ended developmental system, which allows users to interact with the system without losing interest, because it develops new behavior functions through interactions with the environment and users. There were many related research fields such as Predictive Brain Theory,[42] Reinforcement Learning,[43] Imitation Learning,[44] and Language Acquisition study.[45] We focused on robotics-related studies such as MOSAIC,[46] Mimesis,[47] and Dynamical Systems Approach by RNNs,[48] and proposed generalized architecture of those studies as shown in Fig. 23.

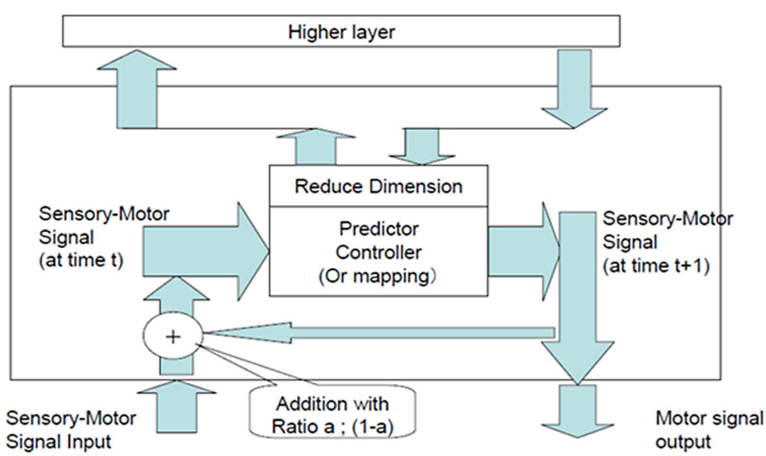


Fig. 23. Generic core model for ID with prediction and controller.

Note that there are three important features in the architecture, which are (i) self-supervised learning with prediction function, (ii) top-down and bottom-up integration in dynamical system, (iii) mental rehearsal with dynamics attractors in the system.

(i) "The predictor/controller" in Fig. 23 can be implemented through Machine Learning technology such as RNN, where the input is sensory–motor signals at time t, and the output is sensory–motor signals at time $t + 1$, both of which can be provided from sensors without human labeling process.

(ii) The bottom-up sensory–motor signal is processed in the predictor/controller to output the signal at time $t + 1$. In parallel, the predictor/controller receives the higher layer information, which is considered as conditional input. In the higher layer, a similar process is executed in the reduced or encoded space to predict the next time slot, which has a longer horizon than the bottom layer so that the longer time prediction can be achieved.

(iii) "Mental rehearsal" can be considered as simulating how well-planned actions can go closer to the goal. There is an internal loop in the system, which is achieved by the addition function of the sensory–motor signal from the environment and the predicted sensory–motor signal from the predictor/controller with the ratio a: $(1 - a)$. Therefore, if the training is properly done, the system can rehearse the time sequence of the future sensory–motor signals without the sensory–motor input from environment. The rehearsal is actually done through dynamics attractors memorized in the system. The mental rehearse can be considered as "World Model", which has been studied in many fields such as Reinforcement Learning, Cognitive Developmental Robotics, Brain Science.[49–52]

Note that we at Intelligence Dynamics Laboratory had the on-premises supercomputer that was ranked in the top-500 in 2004.[53] OPEN-R protocol was well designed with portability of the software so that we can easily connect QRIO to the supercomputer, desk-top PC, or stand-alone system.

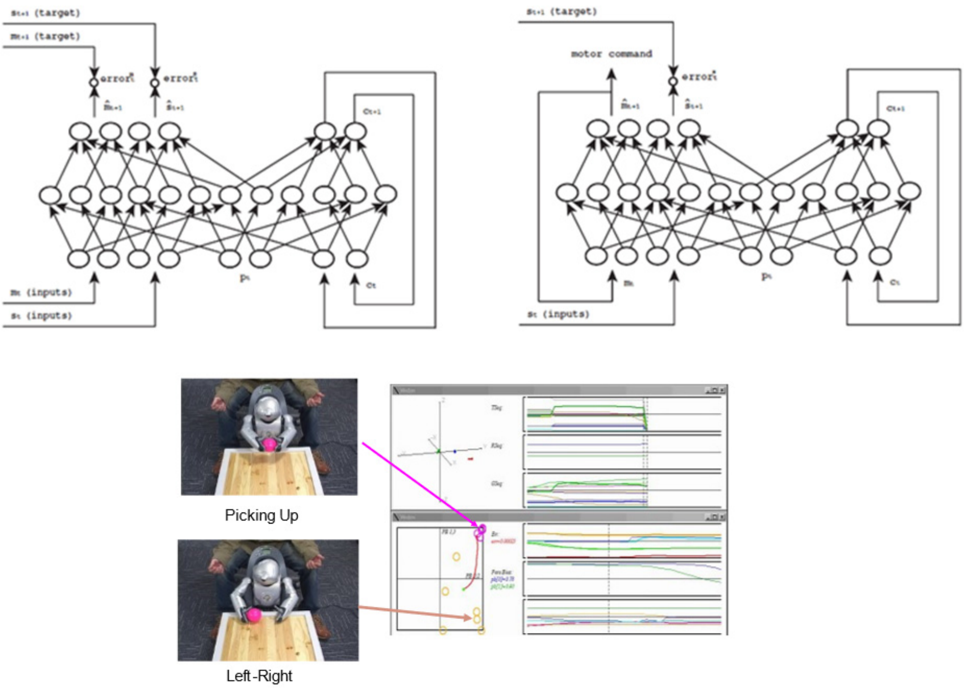
7.1. *Experiments using QRIO with RNN*

While proposing the general prediction architecture of ID, we did some experiments using QRIO to examine the features described above. One example is done with RNN with Parametric Bias (RNN-PB),[54] which shows the experimental results of learned behaviors of QRIO, which are behaviors of picking up a ball (Lift-Up a ball) and rolling a ball in the horizontal directions (Rolling a ball). The training was done by direct teaching by a human, and RNN-PB was used.

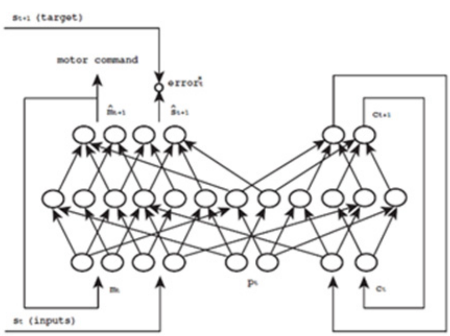
In the ball handling experiment, Fig. 24(c) shows that Lift-Up a ball behavior and Rolling a ball from Left to/from Right are properly memorized in RNN-PB, and the behavior selection and transition are smoothly done without teaching the transition action sequence. PB values are naturally acquired for Lift-Up a ball at the right top corner and "Rolling a ball" from Left to/from Right at the right bottom corner. PB values naturally and smoothly change when the behaviors are in transition.

7.2. *Autonomous cognitive development: Concept*

Using the generic model for ID, we proposed the entire autonomous cognitive development architecture as shown in Fig. 25.[11,12] The right side of the architecture is basically the generic model for ID, which is a layered predictor/controller model. The left side of the architecture is human-designed functions that are similar to

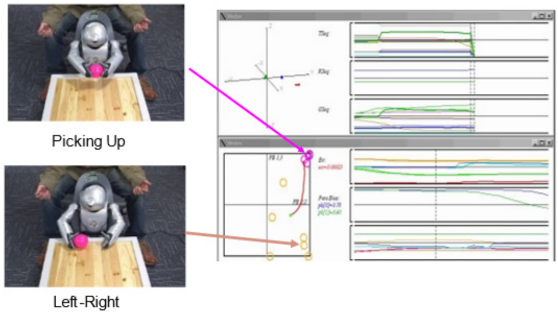


(a) Learning Phase



(b) Interaction Phase

Fig. 24. RNN-PB and dynamics of PB values.



(c) Dynamics of PB Values

Fig. 24. (*Continued*)

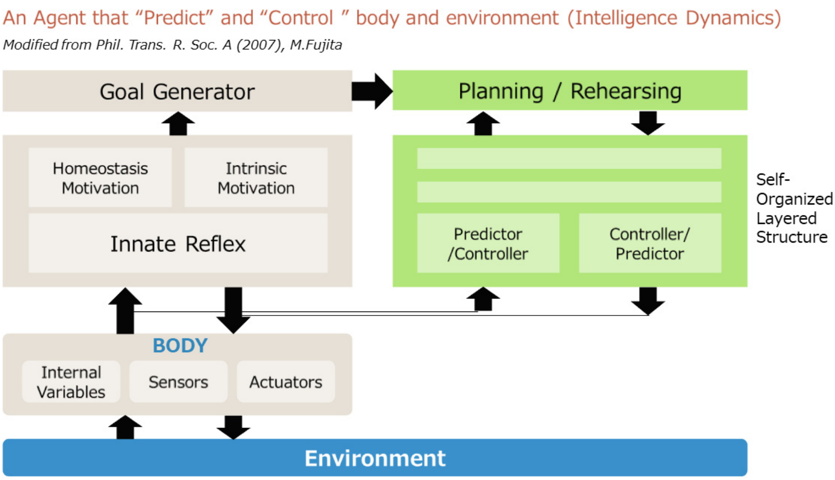


Fig. 25. Autonomous cognitive development architecture: Concept model of ID for open-ended system.

Sec. 3. Innate variables are the same as the internal variable of the ISM of QRIO with sensors and actuators. The functions of the middle of the left are similar to QRIO, which are reflex and homeostasis motivations. Those are necessary to protect and maintain the activities of body.

Intrinsic motivation is not clearly defined in QRIO part. Figure 26 shows the classification of the intrinsic motivation such as curiosity. Those intrinsic motives activate non-body preserving activities, but exploration and development activities of ability of prediction, control, and planning and goal generation. In our architecture, curiosity motive can be the motivation to learn "predictor", and manipulation motive can be the motivation to learn "controller".

Flow[55,56] is another important function for open-ended system. The right part of Fig. 26 explains flow status, where the horizontal axis is a level of skills, and the vertical axis is a level of challenge. If the two levels are in proper relation, the

		Comments
Extrinsic Motive	Physiological	Self-preserve
	Social	Social rewards
Intrinsic Motive	sensory	Seek for stimuli
	Curiosity	Exploration for unpredictable phenomena
	Manipulation	Exploration for object manipulation
	Touch	Seek for stimuli
	Achievement	Achieve a goal
	Affiliation	Being Intimate

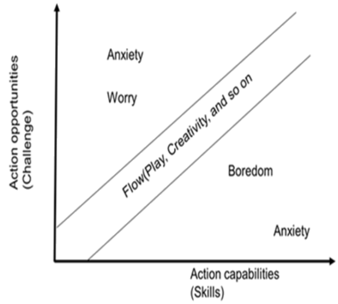


Fig. 26. Classification of motivations in developmental psychology[57] and flow theory.[55,56]

psychological status is called flow, and if a human is in flow status, (s)he keeps learning to increase the level of skills.

Then, a higher challenge target can be attacked. Therefore, based on flow theory the robot agent sets a proper challenge goal considering the already acquired skills.

7.2.1. *Autonomous cognitive development: Preliminary experiments*

We set some agent models with the environment using ID. One of the examples is a pendulum agent as shown in Fig. 27. Please refer to Ref. 58 for more details.

The agent is a one DOF pendulum that can be swung by the applied torque. The torque is not strong enough to swing the pendulum from the bottom ($\theta = 0$) to the top ($\theta = \pi$). Therefore, the controller has to apply the torque properly to swing the agent up. The agent needs energy, which is consumed by applying the torque, and charged by a food set at the top. Lactic acid is a pseudo-muscle fatigue variable.

The goal generator of the agent selects one target variable from (θ, ω, energy level, and lactic acid level), and sets the goal value to the variable. The goal challenge level must be properly set according to flow theory.

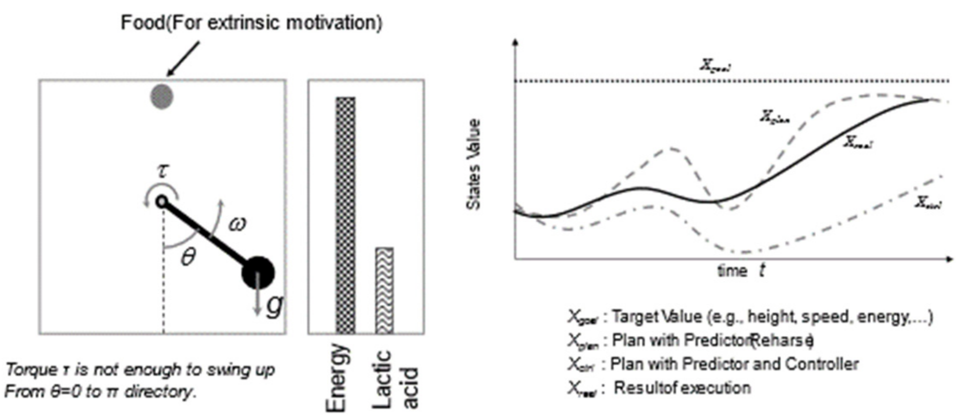


Fig. 27. Pendulum agent experiment setup.

The pendulum agent keeps learning and after some challenges and learning, the agent can visit any position with any velocity, and even stop ($\omega = 0$) at any angles. One of the important learning procedures is to learn the predictor and controller even if the execution is not following the planned trajectory. The graph at the right in Fig. 27 shows a situation, in which planned trajectory by predictor X_{plan}, or by predictor and controller X_{cnt}, is not properly executed in real X_{real}. However, the agent can learn and modify the predictor and controller using the mis-planned trajectory, which will be improved by the real execution.

Thus, our proposal showed that the preliminary experiments with some models could be a potential candidate for open-ended system.

8. PINO as an Open Technology Platform for Commercial Success of Humanoid

As we describe in Sec. 2.2, PINO was aiming at exploring the commercial success of robotics. The strategy was two folds; (i) open platform with inexpensive off-the-shelf components, and (ii) design consciousness to draw people's attention. This section mainly explains the technology.

8.1. *Hardware of PINO*

PINO started to be developed for the RoboCup Humanoid League.[59] Therefore, the mechanical configuration took into consideration soccer playing. The fundamental motions, which are required for the purpose, are (i) keeping its body's balance, (ii) moving the swing leg, (iii) operating grasping object, and (iv) control visual attention.

To meet the requirements, we designed the configuration as follows. Each leg has six DOFs, each arm has five DOFs, the neck has two DOFs, and the trunk has two DOFs. In total, PINO has 26 DOFs. The mechanical design is shown in Fig. 28.

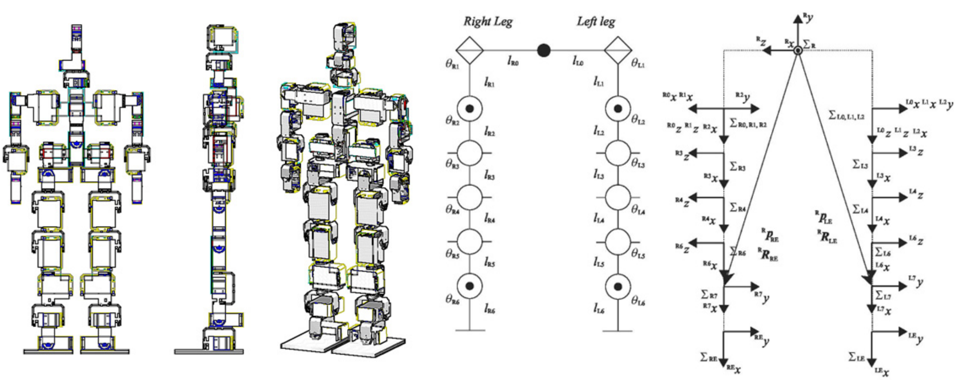


Fig. 28. Mechanical configuration of PINO.

8.2. *Actuators and sensors*

PINO has 26 motors which correspond to the number of DOFs. It needs various kinds of sensors. Examples of this are visual sensors for recognizing objects, posture sensors for detecting its body's balance, force and tactile sensors for detecting contact with others and falling down, and so on. If we were to design all components from scratch aiming at high performance and specific to humanoid, it would be extremely expensive. It is also better to use inexpensive components for actuators and sensors because if a humanoid were to collide with obstacles or fall, resulting in damage, the cost of repairs would be high. There is a servo-module (SM) for a consumer radio control model, an inexpensive, compact, and high torque servomotor. These SMs built in a gearhead and its position controller, and these servo-loops run at 50 Hz. Robots consisting of SMs were already introduced to the market at the time. We adopted two kinds of Futaba SM for PINO with torque rating at 20 kg cm and 8 kg cm [Fig. 29(left)]. All of their gears were changed to metal to reinforce them against high torque.

PINO has eight force sensing register (FSR) [Fig. 29(middle)] attached to each foot which can obtain foot forces and has a posture sensor on its chest so that it can sense its body's posture. We also use potentiometers in SMs as joint angle sensors. PINO also has a vision sensor mounted on its head [Fig. 29(right)]. All information from these sensors is sent to a host computer via A/D converters and a tracking vision board.

8.3. *Processing unit and electric configuration*

The electrical configuration of PINO, shown in Fig. 30, consists of a host computer and a controller of SMs. The host computer obtains all information from sensors via A/D converters and a tracking vision board. The host computer consists of Pentium II 450 MHz processors and 512 MB memory, and its OS is a real-time OS (RT-Linux). Using the information from the sensors, the host computer calculates the angular velocity of each joint in the real time. PINO also has a controller for itself, which consists of a RISC micro-computer Hitachi SH2 (SH7050) and ALTERA Programmable Logic Device (Flex10K30AQC240-3, hereafter PLD).

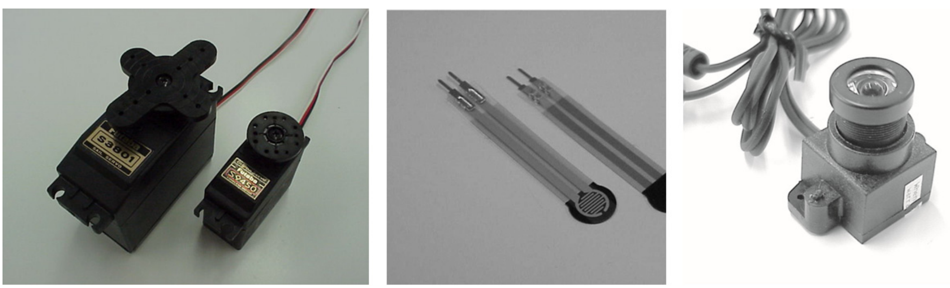


Fig. 29. Actuators and sensors for PINO. (left) Servomotor, (middle) force sensor, (right) vision sensor.

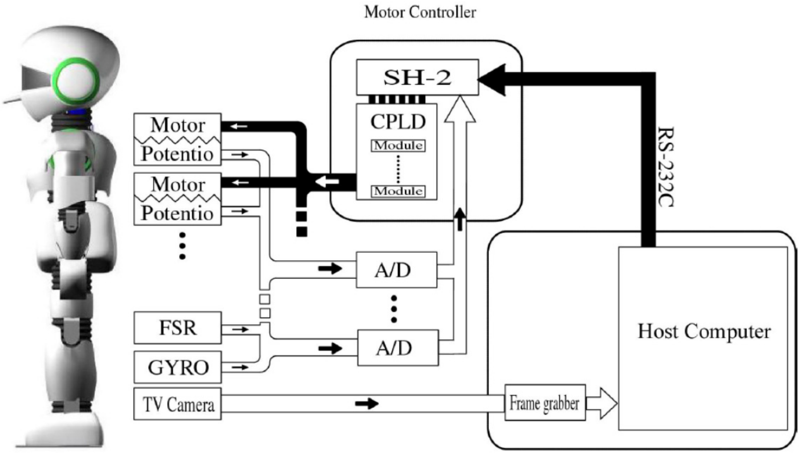


Fig. 30. Electric configuration of PINO.

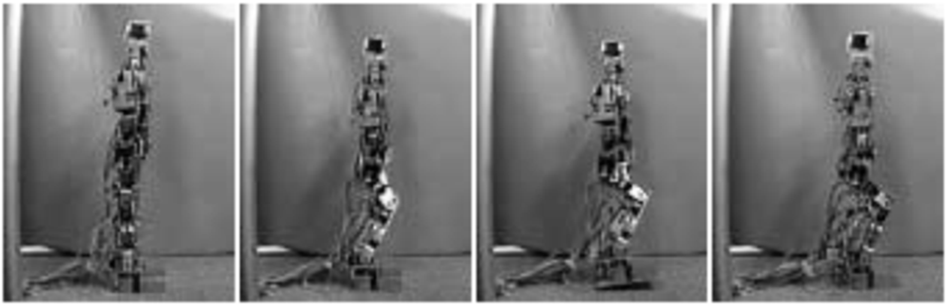


Fig. 31. The first step of PINO's walk.

This controller communicates with the host computer via RS-232C. The PLD has 26 submodules of SM controller in it. Each submodule generates position commands for SM. The servo-loops run at 50 Hz, and the position commands for 26 SMs are updated simultaneously. We can use the development tool for this PLD for free.

8.4. *Control for walking*

Previous work for a legged robot, developed a reflexive walk of a quadruped robot based on reflexes to achieve an adaptive walk in a dynamic environment.[60] They applied two reflexes, a vision-cued swaying refection and a reflective gait, to the robot. A combination of them makes the robot walk reflexively without programing the exact motion of each joint of the legs. Inspired by the non-programing approach for reflexive waking, we conducted at preliminary experiment in which we made PINO walk to give the trajectory of each joint in order to verify PINO's system performance.

We generated the trajectories based on the motion sequence in advance. We gave the trajectories to PINO, and made it walk in a real environment. As a result, PINO can walk based on them. Figure 31 shows the first step of the result of this experiment. In this experiment, PINO often falls down because we only use the interoceptive information. Therefore, it needs to use exteroceptive information in order to achieve adaptive walk. In addition, it is necessary to develop an online system which can generate various kinds of behavior using them.

8.4.1. *GA for walking control*

As the next step, we proposed a two-stage GA[18] for acquisition of stable and smooth walking trajectories for PINO. The fitness function must be a key for the success of GA. We set the fitness function for the first stage at walking distance (longer is better) in order to acquire the continuous walking motion. In the second stage, the fitness function consists of walking distance (longer is better) and energy consumption (less is better) terms to acquire highly energy-efficient walking, and the best results of the first stage are used as the initial individuals for the second stage.

During the walking, the inverted pendulum model and constraint to keep the knee straight are applied to the supporting leg. The inverted pendulum model is known as the highest energy-efficient model for a supporting leg. Since a robot should achieve highly energy-efficient walking using the structural properties of the robot hardware, the supporting leg should be kept straight at the knee joint during the one-leg supporting phase at least. In this case, the supporting leg can be regarded as an inverted pendulum model.

Three trials of the simulation on each stage were performed, and all transitions of fitness values show similar curves. The changes of the best and average fitness values in the first stage of the GA are shown in Fig. 32(left). The second stage of the GA begins with the results of first stage as the initial strings. Figure 32(right) indicates transitions of the best fitness value and the average one at each generation. In this

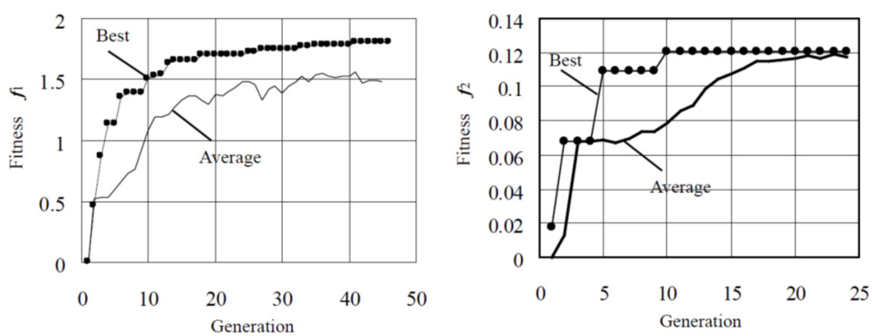


Fig. 32. The maximum and average fitness values in the first stage (left) and in the second stage (right), where $f1$ = walking distance, and $f2$ = (walking distance)/(energy consumption).

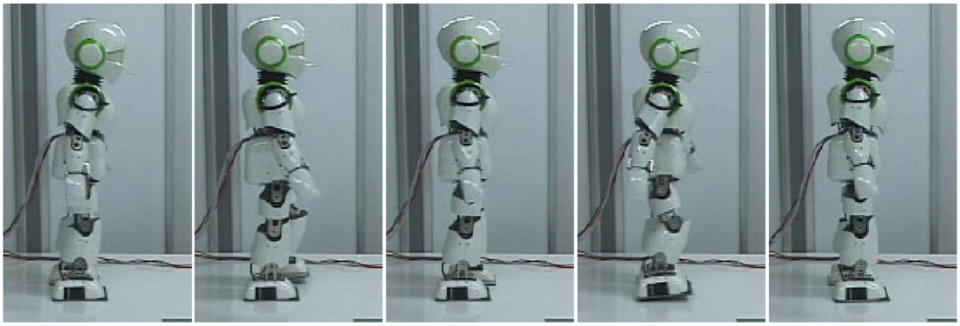


Fig. 33. Walking patterns for PINO generated by the two-stage GA.

phase, the fitness value converges within 25 steps. The generated walking pattern is shown in Fig. 33.

8.4.2. *Co-evolution of morphology and walking pattern*

We tried another GA approach for walking control, which was considering co-evolution of morphology and walking patterns.[19] In the approach, we considered optimum structures of robots which can be designed only when the suitable components and locomotion for the robots are selected appropriately through evolution.

Two steps of co-evolutions were achieved in a precision dynamics simulator using a 3D model. At the first step [Fig. 34(left)], a simple multi-link model is used and the optimal length of each link and walking pattern is obtained. At the second step [Figs. 34(left) and 34(middle)], we assume the servomotors used in PINO and their optimal geometries and walking pattern are obtained. The obtained best morphology is shown in Fig. 34(right), and the generated walking pattern is shown in Fig. 35. The result was useful for improving the morphology of PINO.

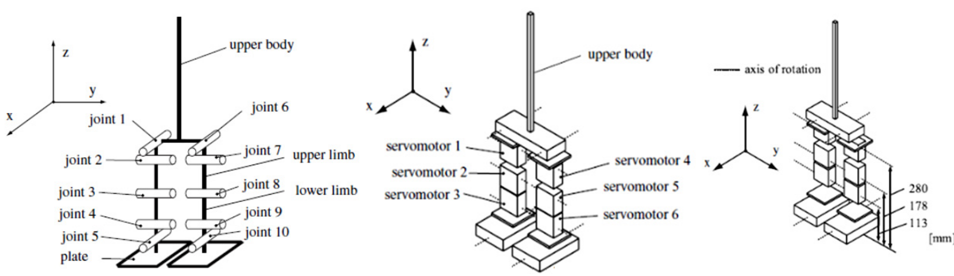
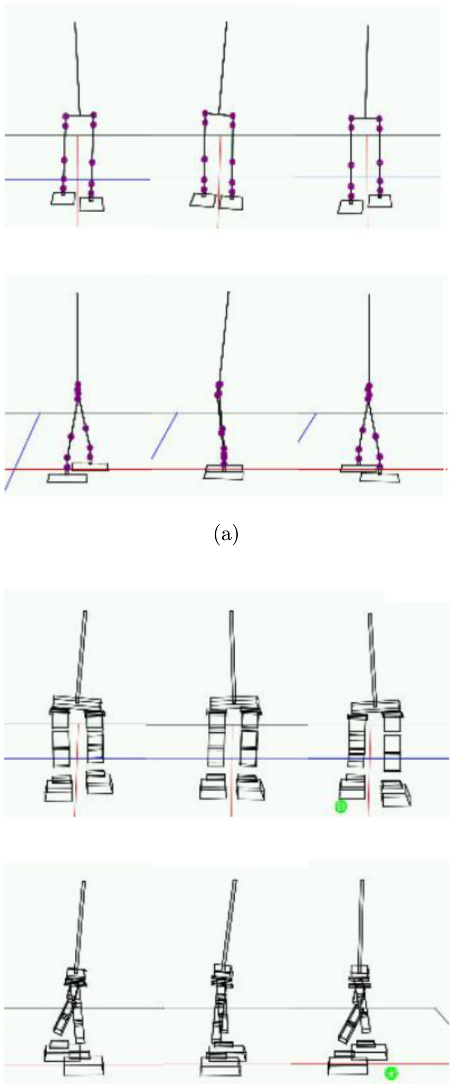


Fig. 34. Morphology of first and second steps, and the best morphology.



(a)

(b)

Fig. 35. Walking pattern of the best robot in the first stage (a) and the second stage (b).

9. Post-PINO Activities

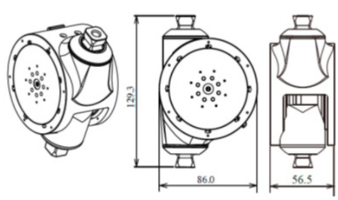
As we described in Sec. 2.2.2, many startup companies for business explorations were launched from the PINO project. In this section, we describe the technologies of some Post-PINO activities.

9.1. *Humanoid technologies for prosthesis*

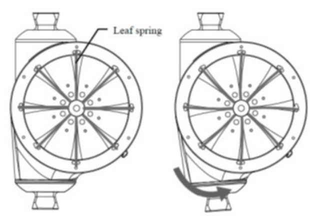
One of the Post-PINO challenges is to develop a prosthesis leg system to augment human physical ability. One example we have been developing is PKP-SEA[23] as shown in Fig. 36. In this study, a PKP with small-scale, light-weight and affordable SEA (PKP-SEA) is developed and adopted to a walking rehabilitation of a patient with four-limb deficiency. A subject is 45 years old and has no experience to walk on prosthetic devices in his life. During the experiment, walking performance is investigated by turning PKP-SEA control parameters. As a result, the PKP-SEA shows the capability of improving walking performance in terms of walking speed and consistency not by replicating normal human walking, but by suggesting an original walking gait based on body condition and remaining functionality.

9.2. *Digital-twin for inspection of infrastructure*

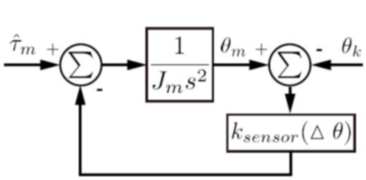
As described in Sec. 2.2.2, consideration of the total cost of the entire workflow is important for the commercial success of robotics. iXs focuses on Inspection of Infrastructure and developing Digital-Twin system of the construction field using SLAM technology with 3D Lidar sensor. A key of the Digital-Twin is to unify 3D information of the design phase called Building Information Modeling/Construction Information Modeling/Management (BIM/CIM) and real-world 3D information by SLAM. Because it is often the case that the design and the real-world information are different, it is necessary to update the BIM/CIM information with real-world 3D information. Furthermore, the information in BIM/CIM with Industry Foundation



(a) Overview of PKP-SEA



(b) Torque and angles displacement of torque sensor



(c) Controller of PKP-SEA

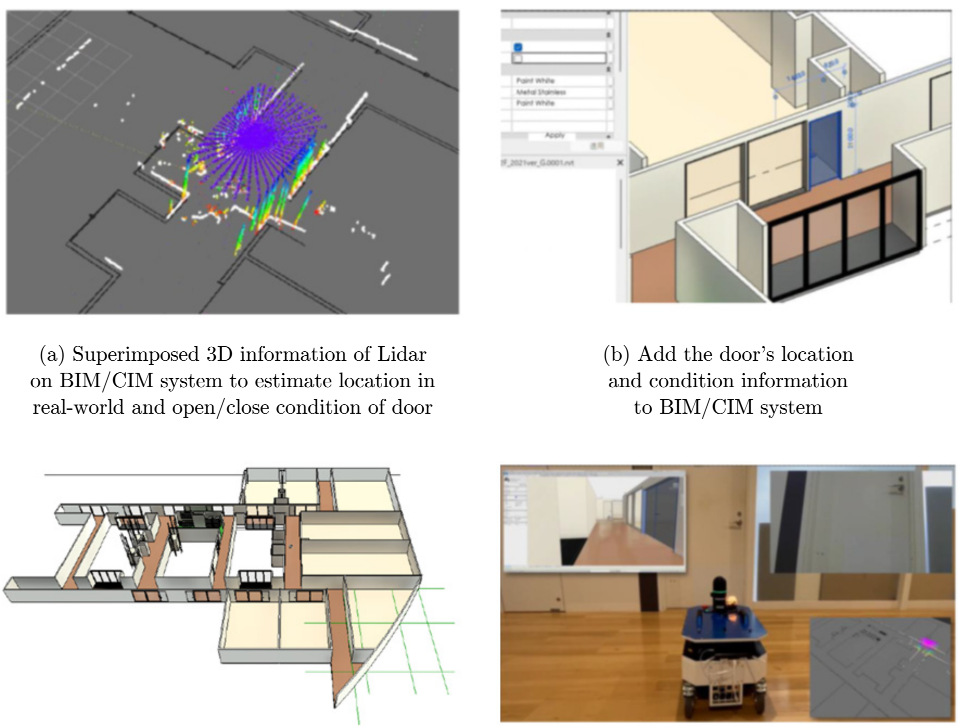
(d) Walking locomotion of the subject with the PKP-SEA

Fig. 36. PKP-SEA. (a) Overview of PKP-SEA, (b) torque and angle displacement of torque sensor, (c) controller of PKP-SEA, and (d) walking locomotion of the subject with PKP-SEA.

Classes (IFC) ISO standard format is also compared with real-world 3D information and registered in the BIM/CIM system.

Once the Digital-Twin of design information and real-world information is thus integrated, we can make the action plan for robots to check the parts' conditions in the BIM/CIM virtual world and execute the plan in the real world. The waypoints of autonomous movements of robots can be assigned in the BIM/CIM virtual world. In our implementation, the waypoints are front sides of door locations.

Figure 37 shows Digital-Twin for Inspection of Infrastructure using BIM/CIM system. Figure 37(a) shows superimposing the Lidar 3D information on BIM/CIM system to confirm the location of the door in the real world and the condition (open/close) of the door. Figure 37(b) shows to add such information of door to BIM/CIM system. Once we build the BIM/CIM system corresponding to real-world states as in Fig. 37(c), then we can efficiently make plans and manage the status of the entire field of infrastructure. We did an experiment to confirm the validity of the Digital-Twin by i-Con Walker.



(a) Superimposed 3D information of Lidar on BIM/CIM system to estimate location in real-world and open/close condition of door

(b) Add the door's location and condition information to BIM/CIM system

(c) Entire field model of BIM/CIM system with real-world information

(d) Experiment with Digital Twin by i=Con Walker

Fig. 37. Digital-Twin for inspection of infrastructure by i-Con Walker.

10. Humanoid Robotics in the 2000s, the 2020s, and Beyond

As we describe the overview of technology progress in Sec. 4, computer performance and communication performance in 2023 have become nearly 1000 times better than in 2000. It makes humanoid robots more intelligent and gives them more flexible mobility even if we use the same technologies. Therefore, what we would like to discuss in this section are items we described for addressing issues related to QRIO, Post-QRIO, PINO, and Post-PINO.

10.1. *Design of humanoid robots*

QRIO and PINO were advanced attempts for addressing an importance of external design of humanoid for intimate interaction with human. As far as humanoid robot is concerned, the external design may not be so emphasized in 2023, yet. Some humanoid robots address a design such as the elderly care robot in Fig. 3(c) (HANAMOFLOR), the androids that communicate without uncomfortable feeling with humans through overcoming uncanny-valley,[61] and the Hugvie with minimal design for comfortable and affinity communication.[62] This is because those robots should not be scary but familiar instead. If humanoid robots work in logistics warehouse without human interaction, functionality may be the first priority. However, if humanoid robots or humanoid robotics technologies are more human-related functions including entertainment robots, we should be aware of the external design again.

10.2. *Actuators and control algorithms*

Actuator, force sensors, and control algorithms have been evolved together. ISA in the 2000s was basically a position control geared motor, and force sensors on soles with control based on ZMP by fast computation algorithms were integrated for dynamic biped walking and dancing. VA in the 2010s was a force control actuator with torque sensor and DSP for force control with DOB in each joint. GID was a whole-body control algorithm to achieve a target dynamical status of the body. GID and VA were used together to achieve the whole-body force reactions. SPEA in 2020 is a force-controlled linear actuator with mechanical springs-dumper. Therefore, compared to legs with a VA joint, it is essentially compliant and safe without control. In addition, a strain gauge for force sensor in VA was fragile because of the nature to detect force as "strain." SEA-type actuator uses position sensors to detect the spring length that is related to the force, therefore it is mechanically robust. The MCDS algorithm has become very flexible with contact points changing in the real time.

One of remaining challenges in this category is integration of a higher layer planner and an MCDS controller. In this context, the higher-level planner means to make a plan for time series of contact points and how to support a body with parts of a body such as paws and soles.

Regarding the computation complexity of GID, MPC, and MCDS, a fast computation for QP solver is necessary. However, because computer performance is getting better and better, and efficient computation methods have been developed, the QP solver becomes almost a real-time solver in GID, MPC, and MCDS. However, if the sensed situation is the same as experienced before, we don't need to solve the QP problem again. It is a generalized approach of computation of value functions in Reinforcement Learning, and actually in ID. Especially in ID, we try to make attractors by which unexperienced status could be pulled in the attractors to go to the known experienced status.

So, we believe that combination of optimization solvers with iterative computations and trained mapping functions without iteration will become an efficient and robust control algorithm in the future.

10.3. *Behavior control architecture*

Recently, LLM with Transformer[33] has made a big impact in many AI fields. Because natural language can be used for Human–Robot Interface (HRI), a user can easily give commands to a robot with high-level and ambiguous expressions. One of the significant features of LLM is that it can be used for a planner.[33,63–65] Some trials have been conducted and reported as better performance in very short period. LLM is basically language model. However, it can handle any vectors or tensors as inputs and outputs. Therefore, multi-modal extensions are intensively studied.[63,65] We will call it Multi-Modal LLM (MM-LLM).

If we compared the MM-LLM robot controller architecture with QRIO's behavior control architecture in Sec. 5.5, there are some functions worth discussing as follows.

10.3.1. *Memory functions of STM and LTM*

QRIO used STM to memorize the surrounding status captured by SLAM and visual recognition, and the objects with the localized information are associated to the LTM information. Therefore, QRIO knows what and where items are. MM-LLM based on Transformer can have a STM as its activation patterns, and a LTM as its network weights. So, theoretically MM-LLM could have the same functions of STM and LTM of QRIO. The design approach of MM-LLM may be different from the classical one such as QRIO, which was designed an architecture by human designers and trained the part functions of the entire architecture. The design approach of MM-LLM can be considered as End-to-End, data-driven approach. However, how to give constraints based on the designers' intention is a key for training. A similar discussion will be in Sec. 10.4.1.

The most important feature of Transformer is Self-Attention. Recently, empirical and theoretical studies have been done for Self-Attention mechanism called In-Context Learning.[66–70] The further studies will clarify the relations between the STM with the LTM association and MM-LLM using Transformer layering by response time requirements.[66–70]

QRIO used three-layered behavior architecture to integrate Reflexive, Situated, and Deliberative behaviors. The response time was about 1–10 ms, 100 ms, and 500 ms, respectively. The behavior layers are computing in parallel, and properly select or coordinate proper actions. If the response time requirements are solved by MM-LLM approach, it is a big step for intelligent robot systems.

10.3.2. *Behavior interruption, preemption, and resume function*

QRIO's behavior control system was designed for multi-user interaction. Therefore, it has the functions that are similar to system OS. The interaction could be achieved by MM-LLM, however; preemption and resume may be difficult for one MM-LLM. System approach to memorize and retrieve the behavior intermediate results may be an easy solution.

10.3.3. *Knowledge utilization such as physics law (Newton's motion equation)*

We used Newton's laws to control QRIO as beforementioned. MM-LLM could find the law if trained with huge data. As we described in Sec. 8.4, a data-driven approach such as GA or ML-LLM is good, but it is easy to start from the basic laws to use a nominal mode. Moreover, if we can use the basic laws as the constraints for ML-LLM, there is a significant progress for MM-LLM. Recently, graph neural networks (GNN)[71–73] approaches are well studied, because Transformer can be considered as GNN. We look forward to further studies.

10.3.4. *External function utilization*

If we ask LLM what the tower of Hanoi solver algorithm is, it answers correctly. However, if you give a concrete tower of Hanoi problem with some large scale, the answer would be wrong. The current MM-LLM cannot use an algorithm that is known by itself. If MM-LLM can use external tools, many solved problems can be handled by MM-LLM. Recently, the systems using APIs of LLM are released,[74] which can be considered as the external function utilization.

10.4. *Developmental learning*

The current approach of LLM, or the Foundation model, is basically off-line training with a huge amount of data (pre-training data). The MM-LLM model for robots is almost the same but the system has to learn new skills in its tasks. Retraining with new data sometimes causes the destruction of the existing trained structure. This issue was historically called as "Plasticity and Stability Dilemma".[75] There are two approaches to solving the Dilemma, which are a monolithic large model approach and modular model architecture approach.

10.4.1. *A large monolithic model approach or module model architecture approach?*

One of the examples of a large monolithic model approach is co-fine-tuning approach.[65] The pre-training data and fine-tuning training data are mixed without increasing total amount of data to acquire the new skills. However, the scalability is not yet proved.

In QRIO, we designed the behavior modules manually and integrated them using value functions to select the proper behavior module in the particular situation. This approach was getting heavier computation as increasing behavior modules.

We took on the challenge of this issue in ID, in which development of new skills was a main target. We used a modular architecture and integration approach using Self-Organizing Map[76] and RNN, or HMM.[77] Module approach was good for non-destroying existing structure and generalization for small number of modules. But again, it was difficult for large number of modules. Further studies must be done.

10.4.2. *World model and mental rehearsal*

Recently, world model has attracted renewed attention in AI and robotics.[50–52] As we described in Sec. 7, the mental rehearsal utilizing the attractor structure of RNN in ID was considered as world model, in which the time sequence of sensory–motor features is predicted without sensor inputs. It was useful for an agent to acquire a policy function, or a long horizon predictor, which can be used as a planner. Note that it can be used for predicting internal status or emotional status as well. Thanks to generative AI technologies such as diffusion model,[78] the prediction can be generated as sensor signal space. It means that the prediction generates a video sequence as mental rehearsal.

10.4.3. *Learning strategy by flow theory*

In ID Prediction/Controller architecture with flow theory (learning from easy missions) was the approach for how or when to learn a new skill. The preliminary implementation was done by selecting, executing, and giving-up if training is properly proceeded.[58] It was good result for a preliminary experiment, but it was still difficult for large-sized number of skills. We studied self-regulated learning approaches using maze environment.[79,80] It is still a challenge for large intelligent systems.

10.4.4. *Layering by causal-relationship*

We discussed the layering approach for the response time requirement in Sec. 10.3.1. There is another approach for layering using causal-relationship, which we studied in the pendulum agent as in Sec. 7.2. MM-LLM naturally uses causal-relation with Deep Layering in Transformer architecture. If we consider developmental learning, we should consider both of layering for response time requirement and causal-relationship in developmental learning context.

10.4.5. *Style flexibility*

Robots have a unique point of discussion specific to their design, which is "style flexibility".[2,82] People design robot form or robot configuration depending on the task and the environment. It could be humanoid form, four-legged form, wheel-based form, etc. Then, control parts for those configurations are different each other. In OPEN-R, we defined layer where configuration dependency is virtualized, and physics parameter for dynamics computation are stored in the module. Recent approach by RT-X[81] adopted a different approach, which builds monolithic LLM trained by many different robot configuration data. Here again the two different policies discussed in Sec. 10.4.1 should be considered, which are (i) a large monolithic model approach, and (ii) module model architecture approach. In addition, the other two different policies discussed in Sec. 10.3.3 should be considered, which are (i) utilizing knowledge of Newton law, and (ii) training with huge data of different configuration robots.

10.5. *Digital-twin and double harvest for development and business operation*

The development environment of humanoid robotics has a progressed with simulation software. We will not describe it in detail in this paper, but as we described in Sec. 9.2, Digital-Twin has been a strong tool for both development and business operation with teleoperation technologies. Monitoring, checking, and reporting functions using Digital-Twin system make a real business a very efficient one.

Once Digital-Twin is established we can collect huge data from the real world, and simulate a world in a virtual world, which can again accelerate the improvement of performance, to find hidden problems, and so on. This is called a Double-Harvest loop.[82]

It is very important both for technology development and business operation.

10.6. *Business*

QRIO and PINO were both aiming at commercial business from the beginning of the projects. QRIO could not be launched ultimately, but PINO started some business and created spin-off startup companies as we described in Secs. 8 and 9. Recently, several announcements of humanoid robots have been made by enterprise companies.[83–85] We believe that humanoid robotics or robotics in general should be developed for human augmentation. Actually, robotics for prosthesis described in Secs. 2.2.2 and 9.1 is a clear example. The super-precision bilateral robotics described in Sec. 2.1.2 is also clearly augmenting human ability.

A labor shortage is currently a serious issue in many industry domains such as factories, logistics, construction, restaurants, and so on. Robots are now trying to introduce those applications. However, we should consider whether or not a human shape such as biped and double arms with hands is necessary. The priorities of external design and functionality depend on where a humanoid works, and how it interacts with humans.

Finally, how about Entertainment Robotics? We believe that it will become important in elderly care centers because of a labor shortage. In addition, people tend to communicate with robots rather than humans because of the mental barrier of communications such as in hospital for children. Humanoid or animal-type robots will be popular in those applications.

10.7. *AI and robotics ethics*

AI ethics have been deeply discussed and many principles were created in major IT companies and institutions. We also released the Sony Group AI Ethics Guidelines[86] in 2018 and establish AI ethics committees, and governance process. Our guidelines and governance process include robotics case as well. Most of the possible harms by robots can be the same as typical data-driven-type AI such as privacy, copyright, fairness, transparency, accountability, and protection from malicious use. Please see the guidelines[86] for more details. In addition, physically movable robots can do physical harm to users and the environment. The problem of job loss could be one of the issues we have to discuss carefully if we introduce robotics technologies into our society.

11. Summary

We described two small humanoid projects QRIO and PINO in about 2000. The projects created many advanced technologies and people who took on the challenge of novel business and technologies. After 20 years, AI and robotics are now at a turning point such as MM-LLM. We discussed and compared QRIO/PINO in the 2000s and the latest technologies in the 2020s. We realized that there are still many challenges remaining. However, it is worth revisiting the technologies in the 2000s and the 2010s, where people tried to solve similar issues, but it was not done perfectly due to something lacking such as DNN and LLM.

We hope that someday humanoid robots will be common in our society to augment human society.

Acknowledgments

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ORCID

Masahiro Fujita https://orcid.org/0009-0006-4646-6975
Yasunori Kawanami https://orcid.org/0009-0002-6426-3451
Kiyokazu Miyazawa https://orcid.org/0009-0003-3449-175X
Masaya Kinoshita https://orcid.org/0009-0004-2343-7085
Kunihito Sawai https://orcid.org/0009-0004-5510-2220
Fuminori Yamasaki https://orcid.org/0009-0004-8217-3833
Hiroaki Kitano https://orcid.org/0000-0002-3589-1953

References

1. AIBO (1999), Wikipedia, https://en.wikipedia.org/wiki/AIBO.
2. M. Fujita and K. Kageyama, An open architecture for robot entertainment, in *Proc. Int. Conf. Autonomous Agents* (ACM, 1997), pp. 435–440.
3. K. Hirai, M. Hirose, Y. Haikawa and T. Takenaka, The development of Honda humanoid robot, in *Proc. 1998 IEEE Int. Conf. Robotics & Automations* (IEEE, 1998), pp. 1321–1326.
4. M. Fujita, Y. Kuroki, T. Ishida and T. T. Doi, A small humanoid robot SDR-4X for entertainment applications, in *Proc. 2003 IEEE/ASME Int. Conf. Advanced Intelligent Mechatronics (AIM 2003)* (IEEE, 2003), pp. 938–943.

5. F. Yamasaki, T. Matsui, T. Miyashita and H. Kitano, PINO the humanoid: A basic architecture, in *RoboCup 2000: Robot Soccer World Cup IV* (Springer, 2000), pp. 269–278.
6. H. Kitano *et al.*, The story of PINO, *Int. J. Humanoid Robot.* **1** (2004) 449–463.
7. ROS, ROS-Robot Operating System, https://en.wikipedia.org/wiki/Robot_Operating_System.
8. M. Fujita, H. Kitano and K. Kageyama, Reconfigurable physical agents, *Robot. Auton. Syst.* **19** (1999) 119–132.
9. K. Nagasaka, Sony QRIO, in *Humanoid Robotics: A Reference* (Springer, 2019), pp. 187–200.
10. M. Fujita, K. Sabe, Y. Kuroki, T. Ishida and T. T. Doi, SDR-4X II: A small humanoid as an entertainer in home environment, in *Robotics Research, The Eleventh Int. Symp.* (Springer, 2005), pp. 355–346.
11. M. Fujita, How to make an autonomous robot as a partner with humans: Design approach versus emergent approach, *Philos. Trans. R. Soc. A, Math. Phys. Eng. Sci.* **365** (2007) 21–47.
12. M. Fujita, Intelligence dynamics: A concept and preliminary experiments for open-ended learning system, *Auton. Agents Multi-Agent Syst.* **19** (2009) 248–271.
13. H. Suzuki *et al.*, Development and testing of force-sensing forceps using FBG for bilateral micro-operation system, *IEEE Robot. Autom. Lett.* **3** (2018) 4281–4288.
14. Y. Kamikawa *et al.*, Tachyon: Design and control of high payload, robust, and dynamic quadruped robot with series-parallel elastic actuators, in *IEEE Int. Conf. Intelligent Robots and Systems* (IEEE, 2021), pp. 894–901.
15. N. Takasugi *et al.*, Real-time perceptive motion control using control barrier functions with analytical smoothing for six-wheeled-telescopic-legged robot Tachyon 3, preprint (2023), arXiv:2310.11792 [cs.RO].
16. K. Nagasaka *et al.*, Whole-body cooperative force control for a two-armed and two-wheeled mobile robot using generalized inverse dynamics and idealized joint unit, in *IEEE Int. Conf. Robotics and Automation* (IEEE, 2010), pp. 3377–3383.
17. K. Nagasaka, T. Fukushima and H. Shimomura, Whole-body control of a humanoid robot based on generalized inverse dynamics and multi-contact stabilizer that can take account of contact constraints, in *Proc. 17th Robotics Symp.* (2012), pp. 134–141 (in Japanese). The Japan Society of Mechanical Engineers (JSME), The Robotics Society of Japan (RSJ), and The Society of Instrument and Control Engineers (SICE).
18. F. Yamasaki, K. Endo, M. Asada and H. Kitano, Control design principle of a low-cost humanoid system using a genetic algorithm, *Adv. Robot.* **17** (2003) 779–790.
19. K. Endo, T. Maeno and H. Kitano, Co-evolution of morphology and walking pattern of biped humanoid robot using evolutionary computation. Consideration of characteristic of the servomotors, in *IEEE/RSJ Int. Conf. Intelligent Robots and Systems* (IEEE, 2003), pp. 2678–2683.
20. ZMP Inc., ZMP: Robot of Everything, https://zmp/co.jp.
21. Flower Robotics Inc., http://www.flower-robotics.com.
22. XiBorg Inc., https://xiborg.jp/en.
23. K. Endo, E. Swart and H. Herr, An artificial gastrocnemius for a transtibial prosthesis, in *Annual Int. Conf. IEEE Engineering in Medicine and Biology Society* (IEEE, 2009), pp. 5034–5037.
24. iXs Co., Ltd., https://www.ixs.co.jp.
25. K. Sawai, The design process in “QRIO”, *J. Robot. Soc. Jpn.* **22** (2004) 979–983.
26. C. A. Mack, Fifty years of Moore’s law, *IEEE Trans. Semicond. Manuf.* **24** (2011) 202–207.

27. Apple, Apple A17 Pro (2023), https://www.apple.com/iphone-15-pro/specs/.
28. Wikipedia, WiFi, https://en.wikipedia.org/wiki/Wi-Fi.
29. M. Inaba, S. Kagami, F. Kanehiro, Y. Hoshino and H. Inoue, Platform for robotics research based on the remote-brained robot approach, *Int. J. Robot. Res.* **19** (2000) 933–954.
30. J.-S. Gutmann, M. Fukuchi and M. Fujita, A modular architecture for humanoid robot navigation, in *IEEE-RAS Int. Conf. Humanoid Robots* (IEEE, 2005), pp. 26–31.
31. S. Dodge and L. Karam, Human and DNN classification performance on images with quality distortions: A comparative study, *ACM Trans. Appl. Percept.* **16** (2019) 1–17.
32. R. Bommasani *et al.*, On the opportunities and risks of foundation models, preprint (2021), arXiv:2108.07258v3 [cs.LG].
33. A. Vaswani *et al.*, Attention is all you need, in *31st Conf. Neural Information Processing Systems* (Curran Associates, 2017), pp. 1–11.
34. K. Nagasaka *et al.*, Motion control of a virtual humanoid that can perform real physical interaction with a human, in *IEEE/RSJ Int. Conf. Intelligent Robots and Systems* (IEEE, 2008), pp. 2303–2310.
35. K. Aoyama and H. Shimomura, Real world speech interaction with a humanoid robot on a layered robot behavior control architecture, in *Proc. 2005 IEEE Int. Conf. Robotics and Automation* (IEEE, 2005), pp. 3814–3819.
36. M. Fujita, AIBO: Toward the era of digital creatures, *Int. J. Robot. Res.* **20** (1999) 781–794.
37. T. Sawada, T. Takagi, Y. Hoshino and M. Fujita, Learning behavior selection through interaction based on emotionally grounded symbol concept, in *IEEE/RAS Int. Conf. Humanoid Robots* (IEEE, 2004), pp. 450–469.
38. K. Miyazawa, Actuator, US20220149695A1 (2022).
39. G. Mathijssen, D. Lefeber and B. Vanderborght, Variable recruitment of parallel elastic elements: Series–parallel elastic actuators (SPEA) with dephased mutilated gears, *IEEE/ASME Trans. Mechatronics* **20** (2015) 594–602.
40. M. Grimmer, M. Eslamy, S. Gliech and A. Seyfarth, A comparison of parallel- and series elastic elements in an actuator for mimicking human ankle joint in walking and running, in *Proc. IEEE Int. Conf. Robotics and Automation* (IEEE, 2012), pp. 2463–2470.
41. B. Penzlin *et al.*, Conceptual design, modeling and control of a rigid parallel serial-elastic actuator, *AT-Automatisierungstechnik* **68** (2020) 410–422.
42. R. Rao and D. Ballard, Predictive coding in the visual cortex: A functional interpretation of some extra-classical receptive-field effects, *Nat. Neurosci.* **2** (1999) 79–87.
43. R. S. Sutton and A. G. Barto, *Reinforcement Learning: An Introduction* (MIT Press, 1998).
44. A. Hussein, M. M. Gaber, E. Elyan and C. Jayne, Imitation learning: A survey of learning methods, *ACM Comput. Surv.* **50** (2017) 1–35.
45. Xiaomeng Ma, Language acquisition and machine learning, in *Mechanisms of Language Acquisition* (Psychology Press, 1987).
46. M. Haruno, D. M. Wolpert and M. Kawato, MOSAIC model for sensorimotor learning and control, *Neural Comput.* **13** (2001) 2201–2220.
47. T. Inamura, I. Thoshima, H. Tanie and Y. Nakamura, Embodies symbol emergence based on mimesis theory, *Int. J. Robot. Res.* **23** (2004) 363–377.
48. J. Tani, Learning to generate articulated behavior through the bottom-up and the top-down interaction processes, *Neural Netw.* **16** (2003) 11–23.
49. D. Ha and J. Schmidhuber, World models, preprint (2018), arXiv:1803.10122 [cs.LG].

50. T. Taniguchi *et al.*, World models and predictive coding for cognitive and developmental robotics: Frontiers and challenges, *Adv. Robot.* **37** (2023) 780–806.
51. Y. Matsuo *et al.*, Deep learning, reinforcement learning, and world models, *Neural Netw.* **152** (2022) 267–275.
52. K. Friston *et al.*, World model learning and inference, *Neural Netw.* **144** (2021) 573–590.
53. E. Stohmaier, H. W. Meuer and J. Dongarra, TOP500 supercomputer for November 2004 (2004), top500.org, https://escholarship.org/uc/iterm/63r51255.
54. J. Tani and M. Ito, Self-organizing of behavioral primitives as multiple attractor dynamics: A robot experiment, *IEEE Trans. Syst. Man Cybern. A, Syst. Humans* **33** (2003) 481–488.
55. M. Csikszentmihalyi, *Creativity: Flow and the Psychology of Discovery and Invention* (HarperCollins, 1997).
56. F. Rheinberg, Intrinsic motivation and flow, *Motiv. Sci.* **6** (2020) 199.
57. H. Azuma, S. Hanta and N. Tajima, *Developmental Psychology Handbook* (Fukumura Publishing, 1992) (in Japanese).
58. K. Sabe, A proposal of intelligence model, MINDY for open-ended learning system, in *12th IEEE-RAS International Conference on Humanoid Robots (Humanoids 2012)* (IEEE, Osaka, Japan, November 29 – December 1, 2012), pp. 18–23.
59. RoboCup Federation, RoboCup Humanoid League.
60. T. Miyashita, K. Hosoda and M. Asada, Reflective walk based on lifted leg control and vision-cues swaying control, in *Proc. 1998 BSMEE Int. Symp. Climbing and Walking Robotics* (Citeseer, 1998), pp. 349–354.
61. H. Ishiguro and F. D. Libera, *Geminoid Studies: Science and Technologies for Humanlike Teleoperated Androids* (Springer, 2018).
62. J. Nakanishi, H. Sumioka and H. Ishiguro, A huggable communication medium can provide sustained listening support for special needs students in a classroom, *Comput. Hum. Behav.* **93** (2019) 106–113.
63. D. Driess *et al.*, PaLM-E: An embodied multimodal language model, preprint (2023), arXiv:2303.03378 [cs.LG].
64. A. Brohan *et al.*, RT-1: Robotics transformer for real-world control at scale, preprint (2022), arXiv:2212.06817 [cs.RO].
65. A. Brohan *et al.*, RT-2: Vision-language-action models transfer web knowledge to robotic control, preprint (2023), arXiv:2307.15818v1 [cs.RO].
66. E. Akyurek, D. Schuurmans, J. Andreas, T. Ma and D. Zhou, What learning algorithm is in-context learning? Investigations with linear model, preprint (2023), arXiv:2211.15661 [cs.LG].
67. W. Yu *et al.*, MetaFormer is actually what you need for vision, preprint (2022), arXiv:2111.11418 [cs.CV].
68. I. Tolstikhin *et al.*, MLP-Mixer: An all-MLP architecture for vision, preprint (2021), arXiv:2105.01601 [cs.CV].
69. H. Liu, Z. Dai, D. R. So and Q. V. Le, Pay attention to MLPs, preprint (2021), arXiv:2105.08050 [cs.LG].
70. A. Mahankali, T. B. Hashimoto and T. Ma, One step of gradient descent is provably the optimal in-context learner with one layer of linear self-attention, preprint (2023), arXiv:2307.03576 [cs.LG].
71. F. Scarselli, M. Gori, A. C. Tsoi, M. Hagenbuchner and G. Monfardini, The graph neural network model, *IEEE Trans. Neural Netw.* **20** (2009) 61–80.
72. Z. Wu *et al.*, A comprehensive survey on graph neural networks, *IEEE Trans. Neural Netw. Learn. Syst.* **32** (2021) 4–24.

73. J. Zhou *et al.*, Graph neural networks: A review of methods and applications, *AI Open* **1** (2020) 57–81.
74. OpenAI, Function calling and other API updates, https://openai.com/blog/function-calling-and-other-api-updates.
75. M. Mermillod, A. Bugaiska and P. Bonin, The stability-plasticity dilemma: Investigating the continuum from catastrophic forgetting to age-limited learning effects, *Front. Psychol.* **4** (2013) 504.
76. T. Kohonen, The self-organizing map, *Proc. IEEE* **78** (1990) 1464–1480.
77. W. Khreich, E. Granger, A. Miri and R. Sabourin, A survey of techniques for incremental learning of HMM parameters, *Inf. Sci.* **197** (2012) 105–130.
78. F. A. Croitoru, V. Hondru, R. T. Ionescu and M. Shah, Diffusion models in vision: A survey, *IEEE Trans. Pattern Anal. Mach. Intell.* **45** (2023) 10850–10869.
79. K. Kawamoto, Y. Hoshino, K. Noda and K. Sabe, Self-regulation mechanism for continual autonomous learning in open-ended environments, in *Proceedings of the Ninth International Conference on Epigenetic Robotics* (EpiRob, Venice, Italy, November 12–14, 2009), pp. 73–80.
80. Y. Hoshino, K. Kawamoto, K. Noda and K. Sabe, Self-regulation mechanism: A principle for continual autonomous learning in open-ended environments, *J. Robot. Soc. Jpn.* **29** (2011) 77–88 (in Japanese).
81. A. Padalkar *et al.*, Open X-Embodiment: Robotic Learning Datasets and RT-X Models, preprint (2023), arXiv:2310.08864 [cs.RO].
82. H. Hotta and K. Obara, *Double Harvest* (Diamond Inc., 2021) (in Japanese).
83. Boston Dynamics, Atlas and beyond: The world's most dynamic robots, https://bostondynamics.com/atlas.
84. TESLA, AI & Robotics (2022), https://www.tesla.com/AI.
85. Figure, FigureAI, https://www.figure.ai.
86. Sony Group Corporation, Sony Group AI Ethics Guidelines (2018), https://www.sony.com/en/SonyInfo/sony_ai/responsible_ai.html.

Masahiro Fujita received his B.S. degree in 1981 from the Waseda University, Japan, and his M.S.E.E. degree in 1989 from the University of California Irvine, USA, in 1989. He joined Sony Corporation in 1981, and worked at the corporate R&D and developed new products such as a GPS receiver for car navigation. After his study of Artificial Neural Networks in the University of California Irvine, he returned to Sony and started a robot entertainment project and developed AIBO and QRIO. He was Founder of AIBO league at the RoboCup from 1998. He was Board Member and Director of Sony Intelligence Dynamics Laboratory Inc. from 2004 to 2007 and led research of developmental intelligent robotics. He became President of System Technologies Laboratory of Sony from 2008 to 2013 and led R&D activities including Machine Learning for image recognition, speech recognition, natural language processing, force control robotics, personalization technologies, cellular communication systems, and security technologies for Sony's services and products. In 2016, he conducted AI and Robotics projects in Sony, including AI $\times$ Gastronomy project, releasing Sony Group AI Ethics Guidelines, and establishment of Sony AI Inc.

Yasunori Kawanami received his M.S. degree in 1999 from the University of Ritsumeikan, Japan. His research was diving robot with arm and impedance control in car steering wheels. He joined Sony Corporation in 1999 and worked for AIBO's mechanical design, firmware, and commercialization, and from 2002 to 2004, he worked for mechanical and exterior designs of QRIO. After AIBO and QRIO projects, he also designed force-feedback haptic device, three fingers manipulation system (ICRA Best Manipulation Award in 2008), elderly nursing robot, power assist, drone (commercialized) and legged robot (Tachyon). Furthermore, he developed motion simulation and Android application software. He is leading various robot projects in AI motion lab.

Kiyokazu Miyazawa received his B.S. degree in Mechanical Engineering from the Waseda University, Japan, in 2003, and his M.S. degree in Precision Engineering from the University of Tokyo, Japan, in 2005. His research was actuators for humanoid robot and planning of graspless manipulation. He joined Sony Corporation in 2005 as Mechanical Engineer, and developed a lot of Sony products such as VAIO and PlayStation. Since 2014, he has been working in Sony R&D developing force-controlled actuators "VA", robot arms, hands, and sensors for medical and service robots. He is responsible for the mobile manipulator project and member of the Robotics Society of Japan.

Masaya Kinoshita received his M.S degree in Control Engineering from the Tokyo Denki University, Japan, in 2008. His representative paper is "Support control to promote skill of riding a unicycle". This research was supported by a Center of Excellence (COE) research project of the Ministry of Education, Sciences, Sports and Culture, Japan, which is entitled "Human Adaptive Mechatronics". He joined Sony Corporation as Software Engineer in 2008 and developed a lot of Sony products such as consumer audio. He has been Leader of the motion control group for legged robots since 2015 and Senior Manager of the Tachyon project since 2022. He specializes in nonlinear control, energy control, and motion generation.

Kunihito Sawai received his M.F.A. degree in 1991 from the Tokyo University of Arts, Japan. He joined Sony Corporation in 1991 and worked for product design, interaction design, and concept making of many Sony products. Examples include a concept design of PlayStation controller, small humanoid QRIO, and the communication robot Xperia Hello!. He received notable awards for his works such as IF Design Award, for Portable DVD Player DVP-FX1, Good Design Award for Personal IT-TV IDT-LF1, Red Dot Design Award Best of Bests for Sound Entertainment Player SEP-1BT.

Fuminori Yamasaki received his Master's degree from the Waseda University in 2000 and Ph.D. at the Osaka University in 2003. From 2000 to 2002, he worked on the project of ERATO Kitano Symbiotic Systems Project as Technical Researcher and developed PINO mechanics, electronics and software. He founded the iXs Co., Ltd. at 1998, and he had deployed investigation robots and decontamination robots to the Fukushima Nuclear Power Plant. Now he focuses on the development of Digital-Twin technology of Social and Industrial infrastructure.

Tatsuya Matsui received his B.A. degree in 1991 from the Nihon University College of Art, Japan. After graduating, he joined the architectural office Kenzo Tange Associates. He later worked in France as Researcher and received his M.A. degree in 1997 from the Ecole Nationale Superieure de Creation Industrielle. In 1998, he worked for Lotus France. Matsui also participated as Member of the research team in the ERATO Kitano Symbiotic Systems program. In 2001, he founded the Flower Robotics and became involved in all stages of the robotics business, from research and development to sales. In 2014, he established Atelier Tatsuya Matsui to undertake a broader spectrum of design and art projects. His awards include the Good Design Award (Japan), ACC Bronze Award (Japan), iF Design Award (Germany), Red Dot Design Award (Germany), and the 6th Nihon University College of Art Award. Some of his solo exhibitions include "Tatsuya Matsui: Robotics" at Art Tower Mito in 2006, "The Space of Flowers and Birds" at the POLA Museum Annex in 2013, and "Re:Play" at the Ise Sekiya in 2014. He is also Visiting Professor at the Nihon University College of Art.

Ken Endo received his B.S. and M.S. degrees in Mechanical Engineering at the Keio University in Japan. He worked as Assistant Researcher on the Kitano Symbiotic Systems Project, ERATO, Japan Science and Technology Corp. from 2002 to 2003. In 2005, he started to work on human biomechanics and development of transtibial prosthesis as Ph.D. student at the MIT Media Lab Biomechatronics group, receiving his Ph.D. in 2012. Currently, he works on augmentation of human physical abilities through robotic technology as Researcher at Sony Computer Science Laboratories. With a colleague, he founded the XiBorg, a company that aims to bring the "delight of locomotion for all people", and serves as CEO. He was chosen as one of the world's most outstanding innovators under the age of 35 by Technology Review in 2012, and selected as a Young Global Leader by the World Economic Forum in 2014.

Shu Ishiguro received his Master's and Ph.D. degrees from the University of Tokyo, in 1998 and 2006, respectively. From 1999 to 2004, he worked on the project of ERATO Kitano Symbiotic Systems Project as Technology Manager. From 2005 to 2010, he was Leader of Robot Laboratory in Osaka City. In 2010, he joined Future Robotics Technology Center (fuRo), Chiba Institute of Technology, Japan. Now he is Deputy Director of fuRo. He was Co-Founder of ZMP Inc. and several startups. Now he is also Co-Founder and Senior Executive Office of JIZAIE Inc.

Hiroaki Kitano is Senior Executive Vice President and Chief Technology Officer of Sony Group Corporation, overseeing the R&D ecosystem across Sony's diverse business, including electronics, semiconductors, and entertainment. Additionally, he is CEO of Sony Research Inc. and Sony Computer Science Laboratories, Inc. (Sony CSL). His work at the Carnegie Mellon University is to build large-scale, data-driven AI systems on massively parallel computers led to The Computers and Thought Award from the *International Joint Conferences on Artificial Intelligence* (IJCAI) in 1993. The quest continued at Sony CSL and at California Institute of Technology gave rise to the field of systems biology, merging biology and systems science. Kitano is Founding President of the RoboCup Federation, President of IJCAI (2009–2011), and Member of scientific advisory boards for numerous academic institutions, including the European Molecular Biology Laboratory (EMBL), and Professor at the

Okinawa Institute of Science and Technology Graduate School. He is a recipient of the Nature Award for Creative Mentoring in Science in 2009 and a Fellow of the Association for the Advancement of Artificial Intelligence. Kitano was Invited Artist for La Biennale di Venezia (2000) and for Workspheres exhibition at the Museum of Modern Art — New York (2001).