# Chapter 1
# Introduction

A humanoid robot is a robot that has a human-like shape. Since many robots in scientific fictions look like humans, a humanoid robot may be the default of robots for most people. On the other hand, it is difficult to claim that robots should be humanoid robots which are supposed to do some tasks in the real world, considering that aircrafts do not look like birds. The required functions for a robot may determine the optimal shape of the robot.

We have to consider what we expect from robots before we investigate what is the optimal shape of robots. An automobile had become the product that created the largest industry in the 20th century, since it satisfied human desires to go to far places and to enjoy driving itself. We should consider what kinds of the desires robots can satisfy. We claim that robots should be expected to do tasks which we do not want to do and to be our partners to enjoy communications. Considering how to realize the functions of robots, the features of humanoid robots can be summarized as follows; 1. humanoid robots can work in the environment for humans as it is, 2. humanoid robots can use tools for humans as it is, and 3. humanoid robots has a human-like shape.

Let us examine the first feature. The environment of the modern society is designed for humans. For example, the width of corridor, the height of a stair, and the position of a handrail are determined to fit the size and motions of humans. Therefore, we need not modify the human environment for a robot to operate when the robot has a human shape and move like a human. An uneven floor has to be made flat, a narrow passage should be removed and a lift must be available when a robot moves on wheels. It should be more economical to develop humanoid robots than to modify the whole environment.

The second feature should imply a similar effect. Most of tools for humans are designed to be used by humans. For example, the size and shape of chairs are determined to sit on them, and the height of dining tables are decided to eat on them. A driver's cockpit is designed to control a car. The shape of a screw driver or scissors can be operated best by articulated fingers. The tools

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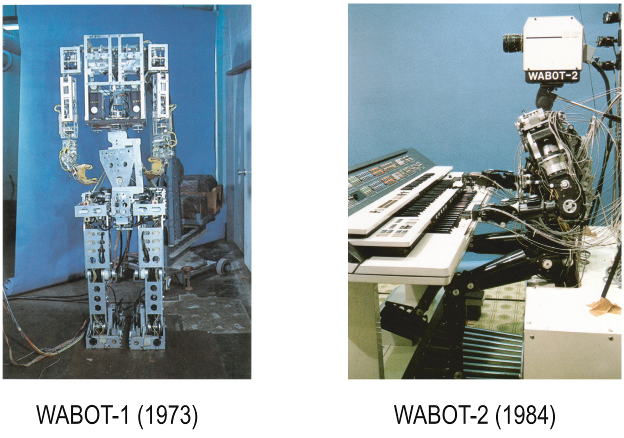
for humans are likely to be used by humanoid robots as it is. It should be more economical to used humanoid robots than to re-design numerous tools.

A similar discussion is written in a novel 'The Caves of Steel' by Issac Asimov. A world famous professor explains why robots should be humanoid robots in the novel and has the similar conclusions with us. Honestly speaking, we need years to reach the conclusions. It is amazing that the same conclusions were already obtained in a fifty-years old novel.

The third feature must need some explanation. A robot is easily personified when the robot looks like a human. The further a robot is from a human shape, the less humans feel a human in the robot. It is fun to watch a biped humanoid robot is dancing, but the dancing of a wheeled robot should be less attractive. A human-like shape is very important to realize a partner robot that can make us enjoy. The third feature must be the primary account why many robots look like humans in scientific fictions. In the real world, WABOT-1 was developed by Ichiro Kato et al. from Waseda University in 1973 (see Fig.1.1).

WABOT-1 could recognize objects by vision, understand spoken language, speak by artificial voice, manipulate the objects by two hands, and walk on biped legs, though the level of the technologies was not so matured. Therefore, it is reasonable to call WABOT-1 *the first humanoid robot.* Ichiro Kato's group also developed WABOT-2 in 1984 which was able to play a piano (see Fig.1.1)[68]D WABOT-2 had played a piano at Tsukuba Science Expo'85 in Japan.

The epoch of humanoids was opened by the astonishing reveal of Honda humanoid P2 in 1996. Honda started a confidential project of humanoid robots in 1986 when one year had passed after WABOT-2 played a piano. P2, 180 cm height and 210 kg weight, is the first humanoid robot that can walk on



WABOT-1 (1973) WABOT-2 (1984)

**Fig. 1.1** Humanoid robots from Waseda University
(Coutesy of Humanoid Robotics Institute, Waseda University)

biped legs with a sufficient stability and mount a computer and battery on the body. Honda published P3, 160 cm height and 130 kg weight, in 1997, and ASIMO, 120 cm weight and 43 kg weight, in 2000. The pictures of P2, P3 and ASIMO are shown in Fig.1.2.

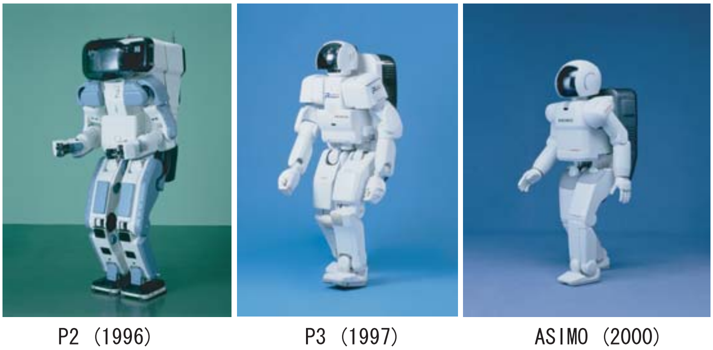


**Fig. 1.2** Humanoid robots from Honda (Coutesy of Honda)

Before P2 was published, the majority in robotics community were pessimistic about the development of a biped humanoid robot that can walk stably. This is the reason why Honda P2 astonished the community. Then what are the major differences between the conventional humanoid robots and P2? Let us examine the hardware at first.

Most humanoid robots developed at universities were made by graduate students or by a small manufacturer. Then the mechanical links of the robots had to be made by bending or cutting and the whole structure was not rigid enough. The reduction mechanisms were implemented by heavy gears with large backlash. By contrast with the old robots, Honda humanoid robots use casted mechanical links with high rigidity and light weight using most advanced mechanical CAD. It was obvious that the casted links should have such properties, but the links were too expensive to be developed by university projects. Honda humanoid robots use harmonic drives which have no backlash. The conventional harmonic drives could transform too little torque to be applied to biped walking, so Honda developed harmonic drives with high torque capacity. After Honda P2 was revealed, most advanced humanoid robots have comparable configurations with those of Honda humanoid robots.

Let us consider the sensors for the robots. Biped walking may not be stable due to disturbance even when the desired walking pattern is planned to make the walking stable. Then the walking should be stabilized by a feedback control that demands appropriate sensors. The humanoid robots developed in the early stage did not have necessary sensors, but Honda humanoid robots have accelerometers and gyroscopes, to find the orientation of bodies and six-axes force/torque sensors to find the contact force/torque between the feet and the floor.

The goal of this textbook is to give the theoretical background for the development of the software to control the well-designed hardware described above.

Chapter 2 overviews the kinematics of humanoid robots. A representation of the motions of the robots is presented after the representation of rotations in three dimensional space, angular velocity vector and the relationship between the derivatives of the rotation matrices and the angular velocity vector are described. It is presented how to find the position and orientation of a link such as a hand or a foot of the robot from given joint angles. The method is called forward kinematics. Then it is explained how to find the corresponding joint angles from given position and orientation of a specific link. The computation is the inverse of the forward kinematics, and is called inverse kinematics. An example of inverse kinematics problems is illustrated in 1.3. When the configuration of the robot shown in 1.3(a) is given, the problem is how to find the corresponding joint angles at which the right foot is raised by 0.3 [m] and rotated by 20 [deg] about $Y$ axis shown in 1.3(b).

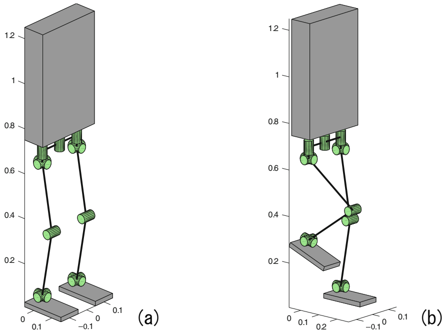
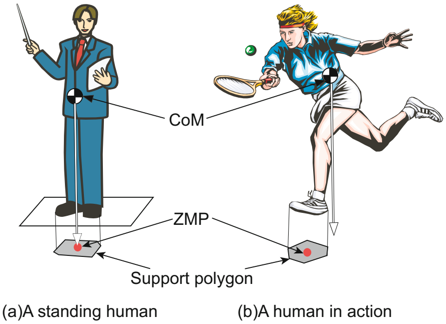


**Fig. 1.3** Example of inverse kinematics of a biped robot; (a) initial configuration, (b) that at which the right foot is raised by 0.3 [m] and rotated by 20 [deg] about $y$-axis

Generally speaking, the postion and orientation of a link and the joint angles are represented by nonlinear equations, since most joints of robots are rotational ones. The inverse kinematics problem can be solve by finding solutions of the nonlinear equations analytically, but it is unlikely to solve the nonlinear equations with many variables and a high Bezout number even if the rotation is parametarized algebraically. However, the relationship between the derivatives of the postion and rotation of a link and those of the joint angles can be represented by linear equations, and the inverse kinematics problem can be solved by finding solutions of the linear equations and integrating the solutions. The coefficient matrix of the linear equations is called Jacobian, which is an important concept in many fields including robotics.

Chaper 3 explains the concept of ZMP (Zero-Moment Point) that plays an important role in the motion control of humanoid robots. When the robot is falling down, the sole of the supporting foot should not contact with the ground any more. The ZMP (Zero Moment Point) proposed by Vukobratović et al. is a criterion to judge if the contact between the sole and the ground can be kept without solving the corresponding equations of motions. The contact is kept if the ZMP is an internal point on the sole. When the robot does not move, the contact is kept when the projection of the center of the mass of the robot onto the ground is an internal point of the sole. See Fig.1.4. The ZMP can be considered to be a dynamic extension of the projection.



(a)A standing human (b)A human in action

**Fig. 1.4** Center of the mass, ZMP and supporting polygon

The ZMP can be used to plan motion patterns that can make the robot walk while keeping the contact between the sole of the supporting foot and the ground. The walking patterns of the majority of humanoid robots have been generated based on the ZMP after Honda P2 appeared.

The robot may not fall down even when the sole of the supporting foot left the ground. It can keep walking or standing by controlling the swing leg and changing the touch down positions. The ZMP criterion is a sufficient condition to prevent the robot from falling down, and not a necessary one. It can neither judge rigorously if the contact is kept when the robot walks on a rough terrain or a stair. When the robot walks while catching a handrail, the contact may be more stable but the ZMP criterion can not tell how much the contact should be made stable. Several trials have been made to extend the criterion, but the generic and rigorous criterion has not been established so far. Chapter 3 presents the concept of the ZMP, the relationship between the contact force and the ZMP, the sensing of the ZMP and an algorithm to compute the ZMP based on the forward dynamics of humanoid robots, which is overviewed as well.

Chapter 4 describes how the walking patterns of biped robots can be generated and the walking can be controlled. Generally, the walking patterns are planned to make the robots walk with no disturbance at first, and a feedback control is applied to stabilize the motions. Various methods have been proposed to general the walking patterns. One method is based on the dynamics of the linear inverted pendulum whose height of the center of the mass is kept by controlling the contact force and the length of the pendulum. Another one generates the patterns using the ZMP as the criterion to judge the contact stability.

Chapter 4 starts from the introduction of a method based on two dimensional linear inverted pendulum, the method is extended to that based on three dimensional one, and it is applied to generate the patterns of multi-link models. Fig.1.5 shows the concept of three dimensional linear inverted pendulum.

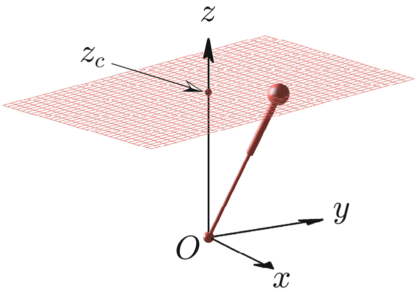


**Fig. 1.5** Concept of three dimensional linear inverted pendulum - the motions of the center of mass is constrained on a specified plane by controlling the contact force and the orientation of the plane is independent to the motions of the center of mass

The ZMP-based method is overviewd as well. The relationship between the derivatives of the joint angles and the ZMP can be given by nonlinear differential equations. It is called the ZMP equations. It is difficult to find trajectories of the joint angles which let the ZMP follow specified ZMP ones due to the nonlinearity. The ZMP equations were simplified under several assumptions and their solutions were found by a batch processing in the early stage. The walking patterns were computed in an offline fashion, even when Honda P2 was published. Honda developed a realtime method to find the patterns and applied it to ASIMO. Nishiwaki et al. invented another realtime algorithm to solve the equations by constraining the motions of the waist joint onto a horizontal plane. Kajita et al. solved the linearized equations in realtime by a preview control and applied it to humanoid robot HRP-2. Chapter 4 explains the methods.

Even when the motion patterns are carefully planned to make the walking stable, humanoid robots may still tip over due to disturbances caused by terrains of the floor, low rigidness of the mechanical structure and the backlash of reduction gears. Therefore, it is demanded to find the status of the robot by sensors including the orientation of the body by an accelerometer and a gyroscope and the contact force and torque of the feet by a force/torque sensor and to apply some feedback control to stabilize the motions. The present configurations of the feedback controllers are the combinations of the orientation control of the body, the control of the center of mass, the compliance control of the feet contact, the impact force control of the foot touch down and so on. The fine tuning of the feedback controllers has become possible since the significant progresses were made in the hardware of the robots as mentioned above. The chapter overviews the principle of the feedback controllers. Fig.1.6 shows the motions of the feet of humanoid robot HRP-2 which walks on a rough terrain with the maximum height of the ramps 2 [cm] and the maximum inclination of the slopes 5 %. The feedback controls are definetely necessary to realize the walking.

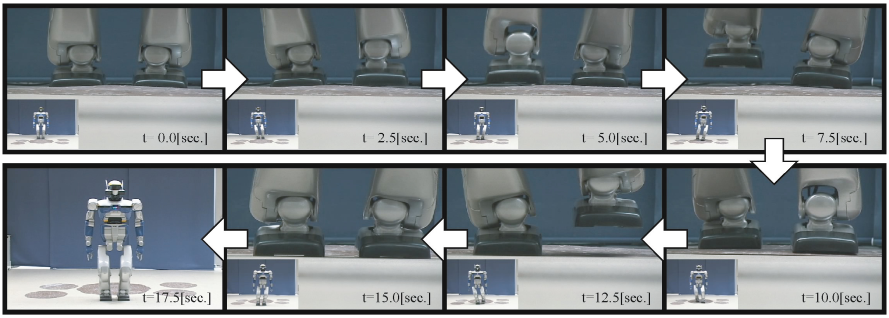


**Fig. 1.6** Feet motions of HRP-2 walking on a rough terrain

Chapter 5 presents how the whole body motions, other than biped walking, of humanoid robots can be realized. Humanoid robots may lie down, get up, carry an object, go through a narrow place and dance. AIST realized the first human-sized humanoid robot that can lie down and get up, which is shown in Fig.1.7.

This chapter overviews how various whole body motions can be generated and controlled. It is described how gross motions of the robots can be generated, including the methods using motion capture systems, graphics user interface and the searching of the configuration spaces of the robots. The methods generate the motions with considering neither the dynamics of the robots nor the contact stability between the robots and the environments, and therefore the motions may not be executed by real robots and the robots may fall down in most cases. Besides, the configurations of the humans whose motions were captured should not identical with those of the real robots. Various methods have been proposed to solve the problems, including the dynamics filters and feedback controllers. The chapter covers the teleoperations of humanoid robots as well.

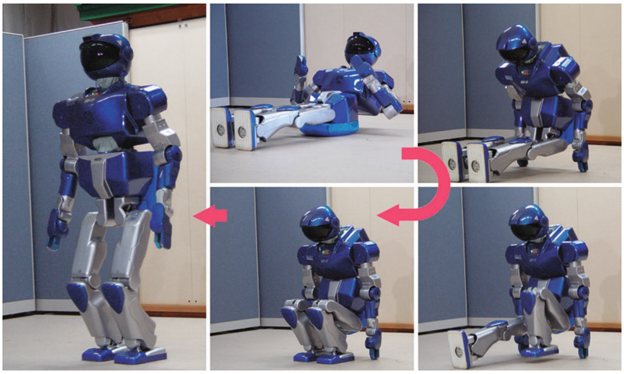


**Fig. 1.7** Getting up of humanoid robot HRP-2P

Though biped robots can go up and down stairs, go over ramps and go through narrow places, the robots may fall down due to the relatively high center of the mass and smaller footprints with serious damage. The advantages of the robots should be enhanced and the disadvantages be conquered to let the robots be accepted in the society. AIST realized the falling motion control of human-sized humanoid robots in Feb. 2003. The motion is like Ukemi motions of Judo that can minimize the damage of the body when a player is thrown by the opponent. The controllable falling motion is limited to the falling backward at present. Sony realized the falling motion control for various falling motions for QRIO, but QRIO is a rather smaller robot than the human-size. The impact of the touch down is significantly larger when a human-sized humanoid robot is falling down, and we should have a tough hardware and a better controller to handle it. Chapter 5 describes the falling motion controller as well as the method to realize the lying down and the getting up.

Chapter 6 presents the algorithms for the dynamics simulation of humanoid robots. The forward dynamics of a robot is the problem to find the updated state of the joints of the robot when the current state of the robot and the generalized force to the joints are given. The inverse dynamics of a robot is the problem to find the generalize force to the joints to realize the desired updated state of the robot. The chapter focuses the attention to the forward dynamics, which starts from that of a rigid body rotating in a gravity-free space and extends the formulation to include the translational motions of the body. An example of the computed motion is shown in Fig.1.8. Finally, we consider the forward dynamics of conneced bodies i.e. robots, which enables the readers to know how the dynamic simulation of humanoid robots can be implemented. The method is based on the Newton-Euler equations, and efficient algorithms to solve the equations were proposed in 1980s. An algorithm developed by Fetherstone will be described as a representative one.

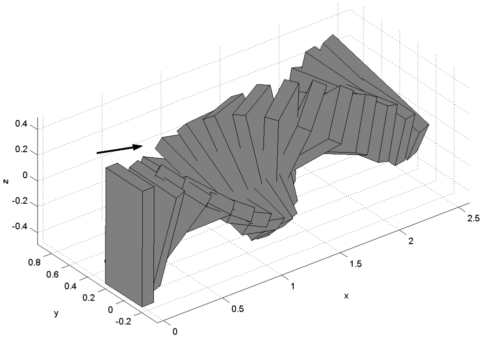


**Fig. 1.8** A computed motion of a rigid body in a gravity-free space

It was the summary of the textbook. The objective of the textbook is to give the foundation to develop the software for controlling the various motions of humanoid robots.

In the following, a perspective of the future of humanoid robotics is overviewed. A humanoid robot can be an integration platform for various robotic technologies, since it has two arms and two legs as well as visual and audio sensors. However, the available computing resource and sensors on the robot should be rather limited due to the space constraint of the robot. We have to make the computers and sensors more compact and powerful to fix the problem. Then more intelligence can be integrated on the platform, and the focus of humanoid robotics may shift from the mobility to the intelligence and the applications based on it.

METI (Ministry of Economy, Trade and Industries) of Japan had run Humanoid Robotics Project (HRP for short) from 1998FY to 2002FY. The leader of HRP was Hirochika Inoue from the University of Tokyo, and HRP developed the fundamental technologies for humanoid robots and explored the applications.

The first feature of humanoid robots is “humanoid robots can work in the environment for humans as it is”, and the maintenance tasks of an industrial plant had been investigated as an example application of the feature. Humanoid robot HRP-1 was able to execute the tasks in a mockup of an industrial plant which includes staris, ramps and pits. Fig.1.9 shows HRP-1 going down stairs in the mockup.

The second feature is “humanoid robots can use tools for humans as it is”, and the driving of an industrial vehicle was examined as an example of its applications. The idea is to realize a teleoperation system for an industrial vehicle by making a humanoid robot drive an industrial vehicle and by controlling the robot by a human operator in a remote space, which can be applied to rescue works. Fig.1.10 shows that a backhoe is drived by humanoid robot HRP-1S which is teleoperated by a human operator. HRP-1S wears a

**Fig. 1.9** HRP-1 going down stairs

**Fig. 1.10** HRP-1S driving a backhoe

waterproof suit. Some amounts of waterdrop can be seen in the picture by a carefull observation.

The third feature is "humanoid robots has a human-like shape", and a trivial application of the feature is entertainment. Honda ASIMO and Sony Qrio have appeared in many commercial messages, and a traditional Japanese dance is reproduced by HRP-2 to realize a digital archive of the dance culture. Another possible application of the feature is a human simulator to evaluate tools for humand like a driver cockpit of vehicles and welfare apparatuses.

Humanoid robotics is in the first exiting epoch after 1996, but it is still very difficult to realize significant products using humanoid robots without passing through a nightmare period.[1] Since humanoid robotics demands a large scale investiment, we have to realize its new applications every five years to continue the efforts. If we aim at the realization of a humand robot whose

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[1] Most innovations had to pass through nightmare periods between that of the fundamental research and that of the industrialization, in which the new technologies were criticized including CAD and industrial robots. Hiroyuki Yoshikawa named the period "a nightmare period" which is an important stage to grow innovations.

ability is comparable with that of a human, we may need a century. We should need a decade at least even if we go ahead to realize an autonomous humanoid robot. From the viewpoint, we would like to propose the goal of 2010 as follows; a humanoid robot that can walk on floors in the daily environment, go up and down stairs and ladders, plan its paths autonomously, fall down without a serious damage, get up from the floor, step over small obstacles, pass through narrow spaces, open/close doors, and manipulate an object by one hand while supporting its body by another hand. It is a humanoid robot that can go any place where a normal human can go. When the mobility is realized, the possible applications of the robot should include the maintenance tasks of industrial plants and the management of hazadous objects. Among the goals, it is most difficult for a humanoid robot to fall down without a serious damage. Even when an appopriate control is applied to the robot when it falls down, the current hardware of the robot is too fragile to keep the mobility. We need much more works to conquer the problem.

Next, as the goal of 2015, we propose the development of autonomous humanoid robots which are able to execute rather simple tasks autonomously that can be done easily by humans. To this end, humanoid robots must have theree dimensional vision that can know the shape, postion and orientation of an object, a dexterous hand that can manipulate various kinds of objects, force/torque sensors that can know the state of the manipulated objects, motion planning and so on. Then the possible applications include assembly of mechanical structures and unregular manipulation tasks. It may be possible to produce more than one thousand copies of the robot when the applications can be realized, and we can claim that we already passed through "the nightmare period" of humanoid robotics.

As the goal of 2020, we propose the development of a humanoid robot that can work cooperatively with humans while sharing the common space with them. The final goal of HRP can be attained when the goal of 2020 is reached. To this end, humanoid robots must have the intelligence for safety as well as high autonomy. It is very difficult to realize the safety, since rather large power should be required for the manipulation and the mobility. It can be understood more comprehensively when we remember that even humans can hart others when a narrow space is shared. The robot should be more safe than a human to be accepted by the society. The efforts like the minimization of the power or the coverage by a soft material are not enough for the purpose, and more sophisticated technologies should be integrated like the realtime observation of the environemnt and the safety control of arms and legs. When the safety intelligence is integrated, it may give a chance to realize the applications like the human care services examined in HRP. It is most difficult to be realized, but the expected sized of the corresponding market should be largest, since the robot can be used at home then. "A humanoid robot for every home" may not be a dream when the mission was completed.

It is very difficult to reach the goal of 2010 from the state of the art in 2005. There is no clear roadmap to attain the goal of 2015. The goal of 2020 is just a dream at present. The objective of this textbook is to let more people learn the foundations of humanoid robotics and spread the use of humanoid robotics. It should be fantastic news for scientists and engineeers that most work in the field of humanoid robotics is still waiting to be done. The development of the automobile replaced the horse as a mobility tool, and the development of humanoid robots offers the promise to replace humans as the bearer of hard and dull tasks. Clearly the goal of humanoid robots alleviating the more burdensome tasks currently performed by humans is both more difficult and potentially more significant than the example of the automobile. We wish that this text may contribute to the ability and inspiration of our colleagues to strive for such a lofty goal.

## The Development at AIST Since 2005

In this section, we present the development at AIST (National Institute of Advanced Industrial Science and Technology) since the previous section was written.

In 2005, we developed biped dinosaur robots with the support of New Energy and Industrial Technology Development Organization (NEDO) and AIST. The purpose was for exhibitions at the 2005 World Exposition Aichi. At the same time, our intention was to seek possible applications of biped technologies in the entertainment industry.

Figure 1.11 shows the developed dinosaur robots [38]. The Tyrannosaurus Rex robot has a body length of 3.5 m from the head to the tail, a weight 83 kg, and 27 DoF (degrees of freedom). The Parasaurolophus robot has the same body length, but it has a weight of 81 kg, and 26 DoF. They are 1/3.5 scale of the real dinosaurs. During the exposition of half a year, these robots successfully performed 1,812 demonstrations and entertained the audience.

As explained in the former section, the Ministry of Economy, Trade and Industry of Japan conducted the Humanoid Robotics Project (HRP) from FY (fiscal year) 1998 to FY 2002. One of the project's outcomes was the humanoid robot HRP-2, which was developed by Kawada Industries Inc., Yaskawa Electric Corporation, the Shimizu Corporation, and AIST [65]. Throughout this book, we will use the HRP-2 as a typical robot to explain the basics of humanoid robotics.

On the other hand, a HRP-2 robot has limitations in its manipulation ability and practical working environment, such as a construction site. To address these limitations, a new humanoid robot HRP-3 was developed in 2007 by Kawada Industries Inc., Kawasaki Heavy Industries, and AIST. This project was supported by NEDO [67]. Figure 1.12 shows the HRP-3, which is a humanoid robot of 1606 mm height, 68 kg weight, and 42 total DoF. For better manipulation ability, the robot has 7 DoF arms and 6 DoF hands (the HRP-2 has 6 DoF arms and 1 DoF hands). In addition, the whole robot and hardware was designed to be dust proof and splash proof in consideration of various environments.

(a) Walking Tyrannosaurus rex robot (Courtesy of AIST)

(b) Parasaurolophus robot (c) The robot and a human

**Fig. 1.11** The dinosaur robots

(a) HRP-3

(b) Manipulation demonstration

(c) Splash-proof demonstration

**Fig. 1.12** HRP-3 and its demonstrations

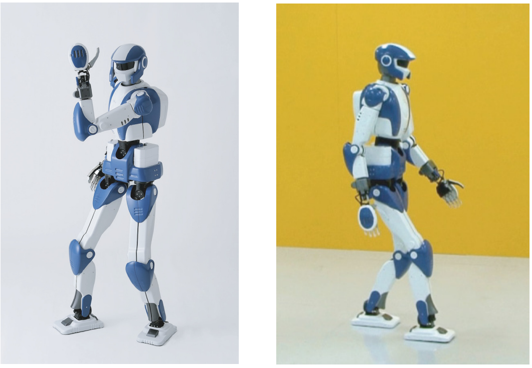
In 2009, we developed a new humanoid robot, Cybernetic human HRP-4C. This robot was designed to have body dimensions close to average Japanese young female [63]. In Fig.1.13(a), we can see HRP-4C has a much more human-like appearance (left) than our previous HRP-2 (right). The purpose of this development was to seek humanoid applications in the entertainment industry, for example, fashion shows. We also intended the use the robot to evaluate devices for humans. Using HRP-4C, we realized human-like walking with toe supporting period (Fig.1.13(b)) [69]. Figure 1.13(c) shows the performance where HRP-4C dances with human dancers. For such performances, we developed a new software for efficient choreography [122]. The hardware of HRP-4C has been modified since 2009, and its current specification is 160 cm height, 46 kg weight and total 44 DoF [64].

(a) HRP-4C and HRP-2 (b) Human-like walk experiment

(c) Dance performance with human dancers

**Fig. 1.13** Cybernetic human HRP-4C

In 2010, another humanoid robot HRP-4 was developed by Kawada Industries, Inc. and AIST. Figure 1.14 shows the robot which has a 151 cm height, 39 kg weight and 34 DoF [64]. HRP-4 was designed as a R&D platform which has a lightweight and slim body compared with our former platform HRP-2. To realize object manipulation better than HRP-2, the robot has 7 DoF arms and 2 DoF hands.



(a) HRP-4 (b) HRP-4 walk experiment

**Fig. 1.14** HRP-4 and its walk experiment

## *Universities and Research Institutes*

Research activities on biped humanoid robots around the world have accelerated in the last decades. In Japan, professor Takanishi's group in Waseda university has been actively developing many biped humanoid robots following professor Kato who built world's first humanoid robot WABOT-1. In 2006, their WABIAN-2R demonstrated impressive human-like walking with knee stretched, heel-contact and toe-off motion [142].

Another prominent group is led by professor Inaba in University of Tokyo. In 2010, they demonstrated HRP-2 which can handle objects of unknown weight based on online estimation of the operational force [123]. They are also developing their original biped robot which can balance even when kicked or otherwise disturbed [52].

ATR Computational Neuroscience Laboratories is studying humanoid robots from a viewpoint of brain science. Using the humanoid robot CB-i developed by SARCOS Inc., their biologically feasible balance controller has been tested [95].

Needless to say, biped humanoid research is not limited in Japan. As remarkable examples, we can see LOLA by Technische Universität of München (TUM) [119], HUBO2 by Korea Advanced Institute of Science and Technology (KAIST) [12], BHR-2 by Beijing Institute of Technology [148], iCub by Italian Institute of Technology (IIT), the University of Genoa [34], CHARLI by Virginia Polytechnic Institute and State University [22], and TORO by the German Aerospace Center (DLR) [15, 16].

## *Companies*

There also exist many humanoid robots developed by companies. Since the surprising debut of the humanoid robot P2 in 1996, Honda, has been carrying on research and development of their ASIMO series. The latest ASIMO unveiled in 2011 can run at 9 km/m, run backward, hop on one leg or on two legs continuously [43].

At the EXPO 2005 in Aichi, a party of robots developed by Toyota Motor Corporation attracted large audiences by their performance in the Toyota Group Pavilion. Some of them were trumpet playing humanoid robots. In 2007, they revealed another humanoid robot which can play the violin [17].

A South Korean company Samsung Electronics, has been also developing humanoid robots with the Korean Institute of Science and Technology (KIST). Their latest humanoid robot is Roboray, which can perform knee-stretched human-like walk [13].

In 2012, an American robotics design and engineering company, Boston Dynamics, developed a humanoid robot PETMAN to test chemical protective clothing [35]. Powered by hydraulic actuators and controlled by advanced control software, this robot can perform squats, squats while turning and side-steps with its arms raised overhead, as well as natural human-like walking of up to 4.8 km/hr.

We cannot purchase above mentioned robots for they were developed as a part of the long range R&D projects. On the other hand, there already exist commercially available humanoid robots for research purposes. For example, Kawada Industries is selling the humanoid robot HRP-4 as a research platform [56]. PAL Robotics in Barcelona has also developed a humanoid robot REEM-C for sale [102].

Currently, there are many small humanoid robots for research and hobby use. For example, we can choose NAO by Aldebaran Robotics [1], DARwIn-OP by ROBOTIS [103], PALRO by FujitSoft [33], or KHR series by Kondo Kagaku Co. Ltd. [4]

## *DARPA Robotics Challenge*

On April 10, 2012, the Defense Advanced Research Projects Agency (DARPA) of the United States announced a program , namely, the DARPA Robotics Challenge (DRC) [3]. It's primary goal is to develop robotics technologies which can manage complex tasks in dangerous, degraded, and human engineered environment by utilizing available human hand tools, devices, and vehicles [5]. DRC is a competition style project where many teams (robots) compete their performances on the same task. In the trial of December 2013, the following tasks were specified.

1. Drive a utility vehicle
2. Travel dismounted

3. Remove debris blocking entry
4. Open a door, enter building
5. Climb an industrial ladder
6. Break through a wall
7. Locate and close valves
8. Carry, unspool, and connect a fire hose

Note that DRC is not limited to the robot configuration being humanoid, but they are expecting human-like competence for the given tasks. Indeed some teams have designed non-humanoid robots like CHIMP by Carnegie Mellon University (CMU) – National robotics Engineering Center (NREC) [2] and ROBOSIMIAN by NASA – Jet Propulsion Laboratory [45]. Yet however, dominant participant teams have chosen humanoid robot designs for this challenge. Moreover, DRC offers an official humanoid robot Atlas developed by Boston Dynamics. Its copies will be used by seven teams. The DRC final will be held in December 2014, and with no doubt, the DARPA Robotics Challenge will have an enormous impact to humanoid robotics research in the world.