Development of the Humanoid Robot ASIMO

Masato HIROSE*　　Toru TAKENAKA*

ABSTRACT

Honda has been conducting research on biped walking humanoid robots as a challenge toward a new field of mobility. This paper discusses ASIMO, the Advanced Step in Innovative MObility developed as a result of our efforts in this field. Our target in this development was a robot that could co-exist with humans and that could actually be useful to humans. This target was achieved through the development of a minimally sized robot (height: 1200 mm, weight: 43 kg) that could conform to a real living environment. Also, by further fostering past research we were able to advance the functionality of the robot. In particular, by adding "free walking technology," which includes predictive control technology, to the existing walking stability control, we were able to achieve a biped robot that can move more smoothly and continuously.

1. Introduction

Since 1986, Honda has been engaged in research on a humanoid robot that would generate new value to human society through coexistence and useful cooperation with human beings. Honda's aim has been to develop a robot that would be able to function in people's living spaces, as part of its program to create innovative mobility. In the course of that research, we obtained gait data from an analysis of human walking, and made use of designs for actuators and mechanisms for bipedal walking, control processes for bipedal walking, and other such technologies to create our P2 prototype cordless biped humanoid robot.[1] The first such robot in the world, the P2, was announced in 1996. In 1997, after studying the place of the humanoid robot in the human life environment and in society, we further completed the P3 prototype model, which is closer to human size.

At the end of October 2000, we brought out the humanoid robot ASIMO (Fig. 1). This is of the minimum size suited to the human life environment (1200 mm in height, 43 kg in weight), and our goal was both to further develop the above technologies and to make a robot that could actually perform useful functions in close association with people. ASIMO, which stands for Advanced Step in Innovative MObility, is the collective name for Honda's humanoid robots. Here we will introduce ASIMO's specifications and the walking technology that gives it the capability for smooth, continuous motion.

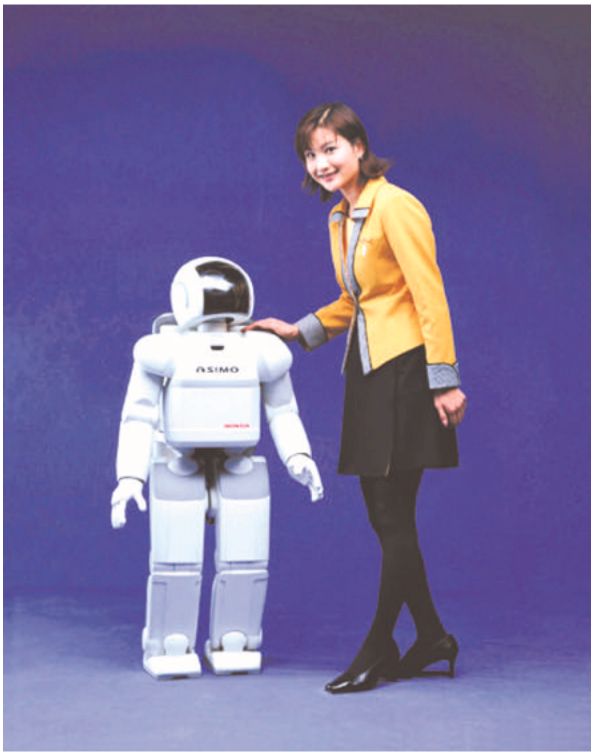

Fig. 1　Humanoid Robot ASIMO

* Wako Research Center

2. Development concept

This project has engaged in research and development of new technologies for the practical application of ASIMO, and particularly the resolution of technical issues in the following three areas:

(1) Compactness and light weight
(2) Advanced arm and hand functions
(3) Enhanced intelligent walking

Size and weight are the most important factors in having a robot function in close association with people in their life environment. It will be necessary to seek greater compactness and lighter weight relative to the previous P3 in order for ASIMO to demonstrate its practicality in the human life environment.

It will also be necessary to expand the compact robot's range of arm motion in order to minimize limitations on its range of activities. In addition, we will have to develop simple mechanisms to make hands capable of grasping objects gently with uniform force.

In order for ASIMO to work in collaboration with humans, we must also develop walking functions and control that enable smoothness of movement in addition to stability in walking. This will be crucial in achieving practical application.

3. Main specifications

3.1 Size

The objective in fabricating the previous P3 prototype was to create a humanoid robot equivalent in size to an adult human. With ASIMO, however, we sought to determine what size a robot should be to actually be useful in the human life environment. The point was for ASIMO not simply to move and transport objects, but also to be of a size suited to its environment. Therefore, we studied the vertical height of arm extension and the squatting position in terms of enabling access to items such as doorknobs, light switches, electric outlets, and other such items in the life environment, as shown in Fig. 2. We also determined the elbow and shoulder locations for ASIMO from work posture at desks and workbenches that we ordinarily use.

ASIMO was given a shoulder height of 910 mm when it stands erect. That location served as the criterion for an upper working space that extends to a height of 1290 mm with ASIMO's arms extended above, and a lower working space that allows ASIMO to work below while crouching. As shown in Fig. 3, the legs had to be 610 mm in length from the hip joint down in order to enable the robot to go up and down stairs. The results of this study led us to make ASIMO 1200 mm in height. The robot's width was set at 450 mm and its depth at 440 mm in consideration of its passage through narrow corridors and doorways. Table 1 compares these sizes with those of the P3. Assigning these dimensions also made the robot more approachable and allows easier communication with it when we are seated on chairs.

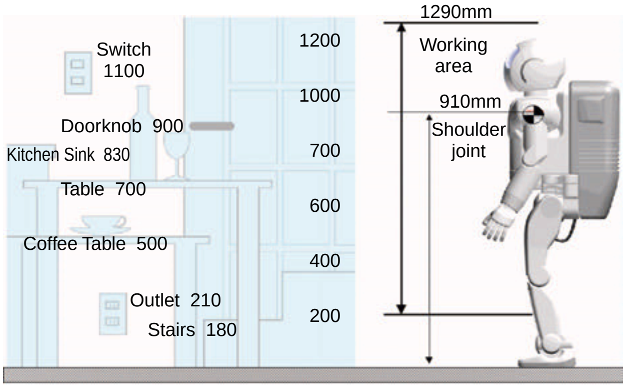

Fig. 2 Life environment and working space

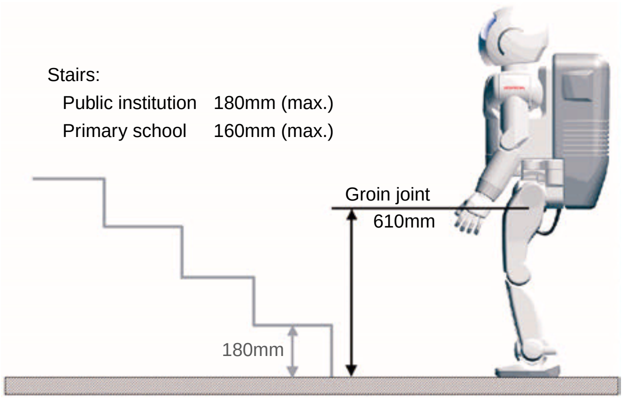

Fig. 3 Stairs

Table 1 Size of ASIMO/P3

	ASIMO	P3
Height (mm)	1200	1600
Width (mm)	450	600
Depth (mm)	440	555
Weight (kg)	43	130

3.2 Weight

As shown in Fig. 4, we reduced ASIMO's bulk and weight relative to the P3, which was 1600 mm in height and 130 kg in weight. Where a weight of 54kg would have followed proportionately from the reduction in bulk, we pressed to make ASIMO lighter by another 20% and achieved a weight of 43 kg. The frame utilizes magnesium alloy materials in an H-shaped cross-sectional structure made up of three-sided elements. The thin-wall casting method was used for the 1.5-mm thick basic structure. The electrical equipment, control units, and so on were also made compact and lightweight by means of optimum design. This robot weighs approximately twice as much as the 22–23 kg of a human being of the same height, but it can be transported by two adults.

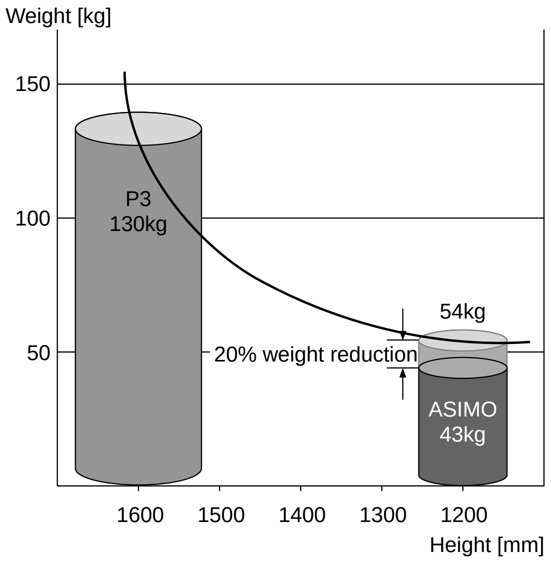

Fig. 4 Weight reduction

3.3 Joint structure

The structure of the joints was determined with reference to the human skeletal structure, while maintaining simplicity and basic movement functions. Fig. 5 shows the joint structures and degrees of freedom. The legs are similar to those of the previous P3 robot in that the ankle, knee, and hip joint structures have six degrees of freedom, and they are of course capable of walking as well as such actions as going up and down stairs and striding over obstacles. The hands, which can open and close their five fingers, have one degree of freedom. The arms are constructed to have five degrees of freedom in the shoulder, elbow, and wrist joints to allow free positioning of handheld implements. The head is constructed with two degrees of freedom to give it the ability to nod.

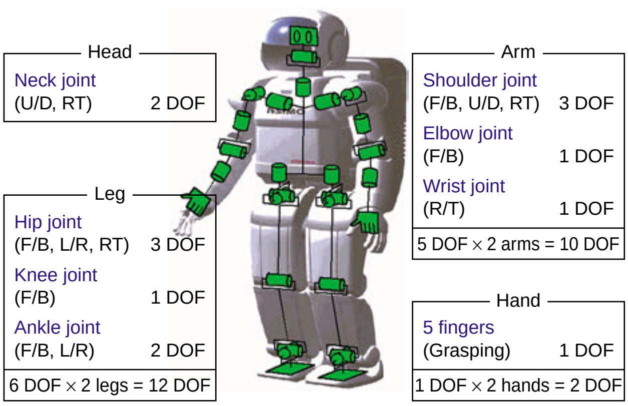

Fig. 5 Joint structure and DOF (Degree of Freedom)

3.4 Arm and hand functions

Study of the work posture of a 1200-mm high robot showed that movements at a high workbench resulted in a posture that brings the elbow joint immediately beside the shoulder joint, as shown in Fig. 6. With this kind of movement, the direction of axial rotation of the shoulder joint and of the elbow joint are in a straight line. This can cause points where their directions of movement overlap, thus restricting the degree of freedom. In order to avoid this limitation, the shoulder joint was built to tilt upward at an angle of 20°, which allows the arm a greater range of movement. As a result, ASIMO can work with its elbow raised as high as 105°, giving it the same working area as the 1600-mm tall P3.

The hand is configured so the five fingers are actuated by pulling a single wire. This makes both grasping and opening movements possible. When the robot starts to grasp an object, one finger will stop on that spot as soon as it comes in contact with the object and the remaining fingers then come in contact with it one after the other in an enfolding movement. In other words, the hand is capable of grasping objects gently with uniform force. The simplicity of the mechanism also improves its access in confined spaces.

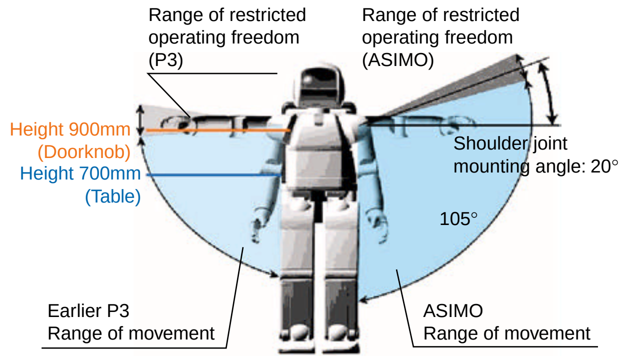

Fig. 6 Range of arm movement

3.5 Operating method

The previous P3 was operated entirely from a workstation. In addition to that method, ASIMO utilizes another, portable remote controller, as shown in Fig. 7, to achieve more intuitive, direct operation.

The use of the workstation as in the past allows startup and standard movements to be carried out automatically. The use of a portable controller makes it possible for the robot to easily perform flexible walking (forward, reverse, sideways, diagonal, turning) . Stored movements (grasping with the hand, waving both hands, waving goodbye, responding with a bow, etc.) can be selected and executed by pressing a button on the portable controller.

3.6 Walking method

As will be discussed in detail in the next section, ASIMO has realized a flexible walking technology that incorporates

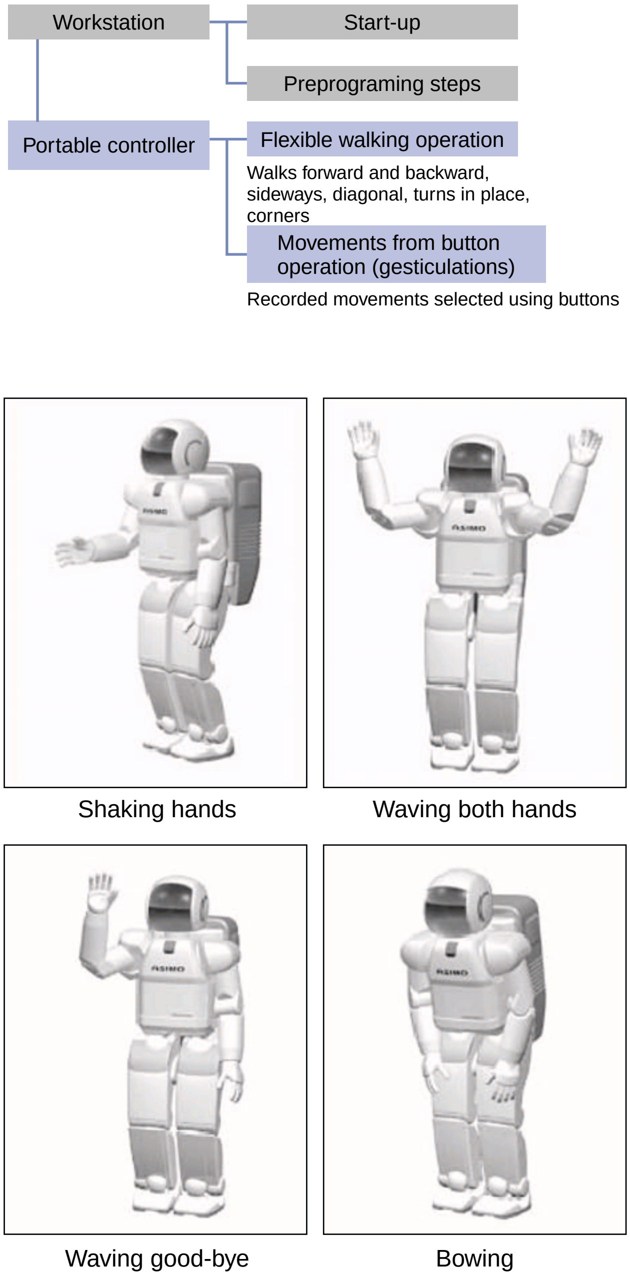

Fig. 7 Operation system

predictive movement control. This is in addition to the walk stabilizing control that was developed in previous research. The new technology has made it possible for ASIMO to change its walking pattern continuously and freely at any moment.

The main specifications of ASIMO described above are shown together in Table 2.

4. Walking technology

4.1 Walk stabilization

When humans are on the point of falling over while walking or standing erect, they (a) push down forcefully on the ground with one part of the sole of the foot, and if that is not enough to hold them up, they (b) change the way they are moving or take a step forward to try and recover their posture. These human movements can be analyzed according to the study of dynamics as follows:

The point where the line of action for the combined gravity and inertia forces intersects with the ground surface is termed the zero moment point (ZMP).[(2)(3)] On the other hand, the point where the ground reaction force operates is known as the central point of the ground reaction force (C-ATGRF). Basically, robots generate their desired walking pattern from that dynamic model using their CPUs, and they walk by making their joints track through the resulting pattern. The ZMP of the desired walking pattern is called the desired ZMP.

While an actual robot is walking in a desirable manner, the line of action of the desired combination of gravity and inertia forces and the line of action of the actual ground reaction force coincide. However, when the robot steps on an uneven ground surface, for example, the lines of action diverge. Then, as shown in Fig. 8, the robot becomes unbalanced and a tipping moment is imposed. This tipping moment is roughly proportional to the discrepancy between the desired ZMP and the central point of the actual reaction force. In other words, the discrepancy between the desired ZMP and the central point of the actual ground reaction force is the greatest cause for loss of balance. The walk stabilization control used in the P2 and P3 instead restored

Table 2 Specifications for ASIMO

Height		1200mm
Weight		43kg
Walking speed		0 ~ 1.6km/h
Walking cycle		Cycle adjustable, Stride adjustable
Grasping force		0.5kg/hand (5-finger hand)
Actuator		Servomotor + Harmonic speed reducer + Drive unit
Control unit		Walk/Operating control unit, Wireless transmission unit
Sensors	Foot	6-Axis foot area sensor
	Torso	Gyroscope & acceleration sensor
Power section		38.4V/10AH (Ni-NH)
Operating section		Workstation or portable controller

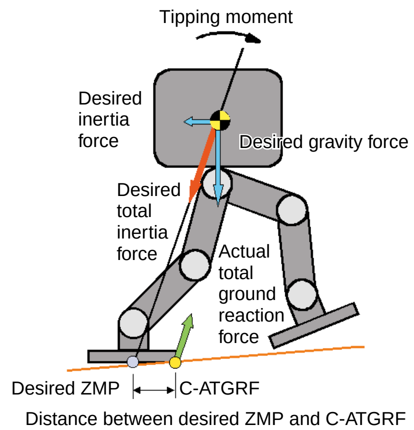

Fig. 8 Unbalance of the legged robot

the posture when the robot lost balance and was on the point of falling over by actively controlling that discrepancy. Ground reaction force control, desired ZMP control and foot landing position control, which are the key technologies in posture stabilizing control, will be discussed below.

4.1.1 Ground reaction force control

Not only does the ground reaction force control absorb unevenness in the ground, but it also acts by controlling the force with which the robot presses the sole of its foot down when it is on the point of falling over. Thus it can be considered a kind of active suspension. In concrete terms, the robot uses the 6-axis force sensor in each ankle to detect the central point of the actual reaction force. While doing this, it changes the positions and the attitudes of the front of the feet, rotating them around the central point of the desired ZMP, in order to control the correct location of the central point of the actual ground reaction force and thus keep a balanced posture. On the kind of unfamiliar upward slope shown in Fig. 9, for example, the central point of the actual ground reaction force shifts toward the front of the feet. However, the ground reaction force control function raises the fronts of the feet slightly to return the central point of the actual ground reaction force to the desired ZMP. When both feet are touching the ground on an unfamiliar upward slope as shown in Fig. 10, the ground reaction force in the forward foot increases and that in the rear foot decreases so that the central point of the actual reaction force ends up shifting forward. The control function then raises the front of the leading foot and lowers the front of the rear foot in order to rotate the fronts of the feet around the desired ZMP and in this way bring the discrepancy back to zero. In addition to making movements that absorb the influence of such unevenness in the ground, the control function also acts when the robot tips forward for some reason, by shifting the central point of the actual ground reaction force to be farther forward than the desired ZMP in order to generate a posture-restoring force. However, the central point of the actual ground reaction force cannot go beyond the area where the soles of the feet are touching the ground. Therefore there are limits to the posture-restoring force, and if the robot tilts very far, it will fall over.

4.1.2 Desired ZMP control

The desired ZMP control operates when the robot tilts significantly to prevent it from falling over. If the robot is in danger of falling forward, for example, the desired ZMP control accelerates the upper body trajectory of the desired walking pattern more strongly forward than the ideal trajectory, as shown in Fig. 11. As a result, the desired ZMP is shifted to the rear of the central point of the actual ground reaction force so that a force is applied to tilt the robot backward and the posture is restored. In other words, the control restores the robot's posture by deliberately unbalancing the desired walking pattern.

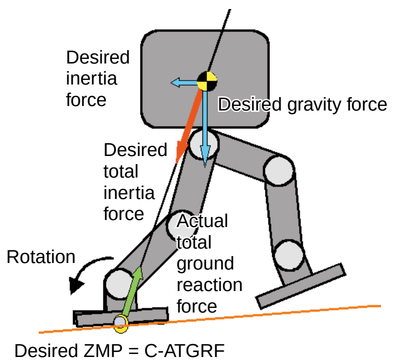

Fig. 9 Compliant motion during single support phase

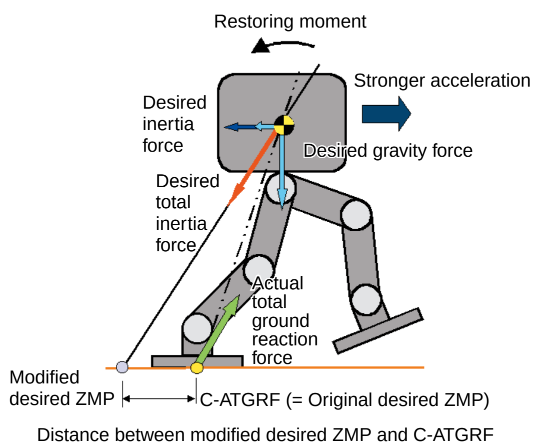

Fig. 11 Model ZMP control

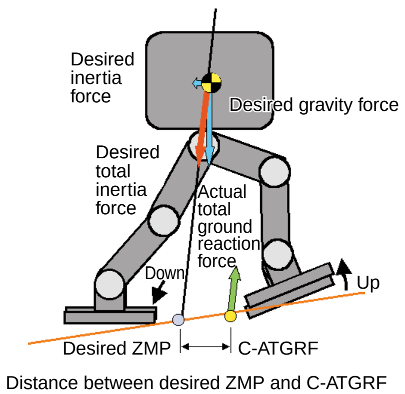

Fig. 10 Compliant motion during double support phase

4.1.3 Foot landing position control

The operation of the desired ZMP control causes the desired position of the upper body to be accelerated more forcefully forward and so to be displaced. When this happens, and the next step is taken with the stride length that was originally ideal, the feet end up being left behind by the upper body. The foot landing position control then operates to correct the stride length in order to bring the upper body and the feet back into an ideal spatial configuration.

4.2 Enhanced intelligent walking

The previous method for generating the robot walking pattern involved designing several dozen kinds of basic walking patterns offline and having the robot memorize them as time-series data. The combination of these data (weighted averages) would then be used to generate flexible walking patterns. There are, however, several drawbacks arising from this principle, such as: (a) the robot must come to a temporary stop while making the transition from straight-ahead walking to a turn; (b) its turning walk is flat-footed; and (c) it is limited to several kinds of walking cycles. These drawbacks were resolved in ASIMO by the development of a new predictive movement control technology that seeks to improve the intelligence of walking.

Let us take the example of a continuous transition from straight-ahead walking to turning. As shown in Fig. 12, it is necessary to shift the center of gravity toward the inside of the turn in order to balance the centrifugal force. When ASIMO makes the transition from straight-ahead walking to a turn, predictive calculations are made starting before the turn to determine the optimum shift of the center of gravity at every instant while generating a walking pattern in real time.

In this way, the previous walk stabilizing control is augmented by incorporating additional predictive movement control to form a new flexible walking technology. Realization of this technology has made it possible to change the robot's walking pattern smoothly, freely, and flexibly at any moment without first coming to a stop.

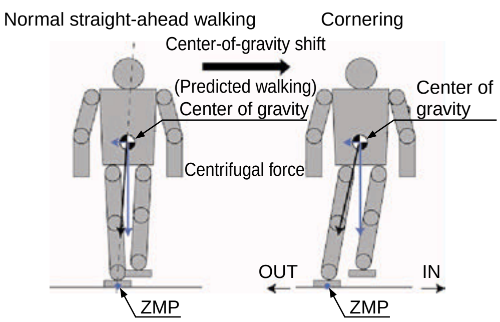

Fig. 12 Center-of-gravity shift when cornering

5. Conclusion

The development of ASIMO realized significant advances in compactness and lighter weight by means of our reassessment of dedicated electrical equipment designs and structures. The newly developed walking technology also gave it the capability for walking flexibly. For the future, we are planning to make further improvements in compactness and motor functions for a robot that will be useful in our life environments, and we will also promote development of advanced intelligence for a robot that can perform a variety of tasks.

We wish to express our gratitude to the many people here and elsewhere who cooperated with us in numerous and important ways on bringing this robot to completion.

References

(1) Hirai, K., M. Hirose, Y. Haikawa, T. Takenaka: The Development of Honda Humanoid Robot, IEEE ICRA (1998)
(2) Vukobratovic, M., Y. Stepanenko: "On the Stability of Anthropomorphic Systems," *Mathematical Biosciences*, Vol. 15, Oct. (1972)
(3) Vukobratovic M., "The Walking Robot and the Man-made Leg," trans. by Kato and Yamashita, Nikkan Kogyo Shinbun Ltd. (1975)

■ authors ■

Masato HIROSE Toru TAKENAKA