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The First Humanoid Robot that has the Same Size as a Human and that can Lie down and Get up

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Abstract

This paper presents a humanoid robot that has the same size as a human and that can lie down to the floor and get up from the floor with the robot face upward and downward. We believe that the robot is the first life-size humanoid robot with the capability. The motions are realized by the combination of novel hardware and software. The features of the hardware are a human-like proportion and joints with wide movable ranges including two waist joints. The software segments the motion into the sequence of the contact states between the robot and the floor and assigns an appropriate controller to each transition between the consecutive states. The experimental results are presented.

1 Introduction

In recent years, more and more research is carried out on humanoid robotics after astonishing Honda P2[2] was revealed. Honda also developed P3 and ASIMO[3] after P2. The University of Tokyo developed H6[12] and H7[7], and various kinds of software are developed using them. Sony developed small size humanoid robots SDR-3X[11] and SDR-4X for entertainment. There are several other humanoid robot including WABIAN[14] from Waseda university, and PINO[15] and MORPH[1] from Kitano Symbiotic Systems Project.

The Ministry of Economy, Trade and Industry (METI) of Japan has also run Humanoid Robotics Project (HRP for short) since 1998FY for five years [6]. The objectives of HRP include the development of the research platform for humanoid robotics consisting of humanoid robots, software platform (called OpenHRP[8]) and teleoperation cockpits and the exploration of humanoid robot applications. In the development of the research platform in HRP, we have developed a humanoid robot that has the same size as a human and that can lie down to the floor and get up from the floor with the robot face upward and downward from the following motivation.

One of the weak points of a humanoid robot is that the robot may tip over because of its features that the center of the mass is relatively high and the size of its feet is small. To cope with the problem, many researches have focused on the methods to improve the stability of the walking. However, it is impossible to prevent the robot from tipping over for its lifetime. Because the robot may collide with an object or a human when it works in our dairy environment that includes many uncertain obstacles and then no controller can always make the robot stand. An alternative way is to let the robot get up from the floor when it tipped over. If such a humanoid robot is realized, the requirements for the walking controller can be relaxed significantly. This is considered to be a kind of fail-safe design of a humanoid robot.

Note that the robot must fall down with the minimum damage before it can get up from the floor. In other words, falling motion control must be applied to a humanoid robot for the purpose, which is also under development[10].

This paper focuses on the latter part, that is, how a humanoid robot that can lie down and get up has been realized. The motions are realized by the combination of novel hardware and software. The features of the hardware are a human-like proportion and joints with wide movable ranges including two waist joints. The software segments the motion into the sequence of the contact states between the robot and the floor and assigns an appropriate controller to each transition between the consecutive states. We believe that the robot is the first life-size humanoid robot that can lie down and get up.

This paper is organized follows. Section 2 surveys related works on getting up motion control. Section 3 describes humanoid robot HRP-2P that satisfies the specifications required for a humanoid robot hardware that can lie down and get up. Section 4 explains the details of the controller for the motions. Section 5 presents the experimental results by HRP-2P. Section 6 concludes the paper.

2 Related Works

There are several pioneering researches on getting up motions of small-size humanoid robots. Within our knowledge, "Hanzou", developed by one of the authors et al., is the first humanoid robot that can get up by itself[4]. It can also continue to walk even after it tips over. Hanzou has 30[cm] height, 2[kg] weight and 16 d.o.f. If it tips over into lying on the back position, it can roll over by swinging its leg. The getting up motion is divided into a sequence of the contact states between the robot and the floor as well as the proposed method in this paper, but each transition between consecutive states is realized by a playback of a fixed motion pattern. Those patterns are designed by considering the static balance of the robot from the geometric model[5].

Sony SDR-3X is 50[cm] height, 5[kg] weight with 24 d.o.f., and can get up with the robot face upward and downward in their simulator[13] and experiments. SDR-4X which is the successor of SDR-3X is 58[cm] height, 6.5[kg] weight with 38 d.o.f., falls down intentionally when pushed by a human, and can get up with the face upward and downward.

So far no life-size humanoid robot is able to get up or lie down. The motion has not been realized yet, partly because we have had no life-size humanoid robot without a large backpack that should prevent the robot from getting up with its face upward and with arms that have enough power and joints with wide movable ranges for the motion. A bottleneck in the software is how to realize the motion that makes the hands of the robot take off the floor from the state in which the robot stands on its hands and knees.

The bottleneck could be removed by introducing a special designed hardware to realize the motion. For example, we can introduce large-size feet or heavy lower half of the body. However, such special hardware may spoil an important advantage of a humanoid robot, that is, a humanoid robot can work in the usual environment for humans since its shape resembles a human. The robot can not go through a narrow place with large feet, or needs more power for the heavy lower half. This paper tries to remove the bottleneck by the software described above while keeping a natural shape of a humanoid robot.

3 Humanoid robot HRP-2P

Humanoid robot HRP-2 is under development in HRP. HRP-2 is designed to have the capabilities including walking on a rough terrain, controlled falling for the minimum damage and getting up from the floor, and going to be applied to cooperative works with a human. HRP-2P[9] is the prototype of HRP-2, and has 154[cm] height and 58[kg] weight that is supposed to have the same size with a human. Figure 1 shows a front view and a side view of HRP-2P.

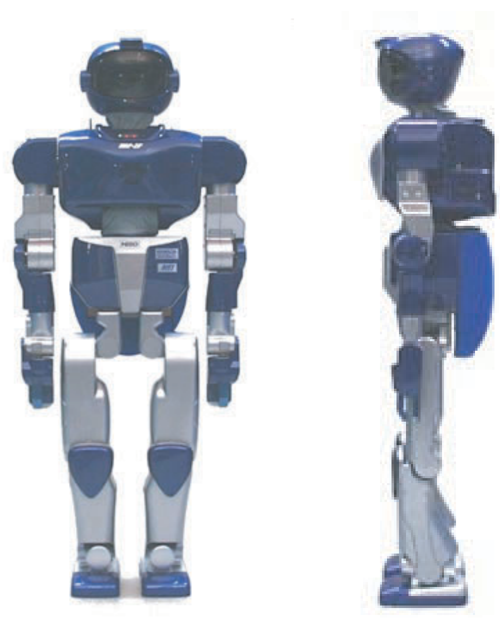

Figure 1: Humanoid robot HRP-2P

The specifications required for the motion include no backpack on the back, a waist joint that can move the upper half of the body forward and backward, wide movable ranges of joints each of which covers the range of the corresponding joint of a human. The details of the specifications are describes in the following.

3.1 Backpack free design

The body of HRP-2P contains the equipment required for its independent operation including computers and batteries, while some of existing humanoid robots need a large backpack for them[2, 3]. The compact shape of HRP-2P has been realized mainly by a high density implementation of electronic parts.

While a humanoid robot tries to get up from the floor, various parts of the body may contact with the floor and the transitions between different contact states must be smooth to realize the motion. For example, a large projection from the body like the backpack should impose difficulty on the robot when it gets up with its face upward. HRP-2P has a human-like proportion without any large projection as shown in Fig.1.

3.2 Waist joint

Figure 2 shows the mechanical configuration of HRP-2P. One of the features of HRP-2P is that it has

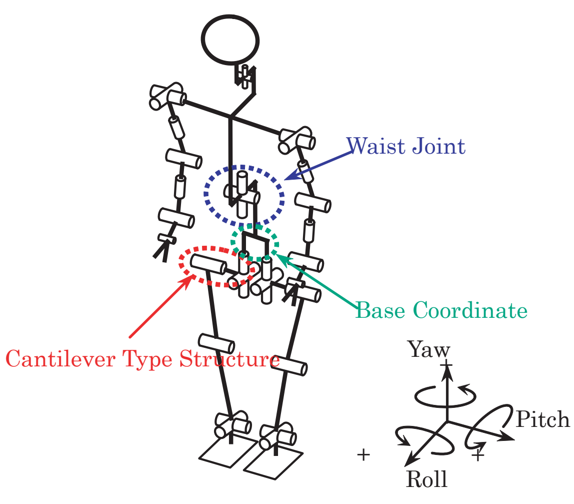

Figure 2: Configuration of HRP-2P

two waist joints. Using the pitch joint of the waist, it can bend its trunk and move the center of the mass of the body in a wide range on the sagital plane. As mentioned above, one of key points for the getting up motion is how to realize the motion that makes the hands of the robot take off the floor from the state in which the robot stands on its hands and knees. In order to realize this transition, the center of the mass must be moved backward while supporting the upper half of the body using the arms. To move the center of the mass backward, the upper body must be raised by bending knee joints.

However, the robot must fall forward when raising the upper body if the robot has a human-like proportion but doesn't have the waist joint. Because the hands leave the ground before the centroid moves backward than the position of the knee joints on the sagital plane. Therefore, the arms must be extended to realize the getting up motion without waist joints, but each arm must have an extra joint and more mechanism for the purpose that breaks the human-like proportion. An alternative is to realize the motion by a dynamic motion. But such a dynamic motion demands joints with powerful torque and imposes a large impact force on the hardware. From these reasons, it is claimed that the waist joint is necessary to realize the motion.

3.3 Wide movable ranges of the joints

At first, we tried to design the movable range of each joint to be about the same as the corresponding joint of a standard human so that the robot should perform the task for human as well. Table 1(a) shows movable ranges of the head, right arm, right hand, waist and right leg of a standard human. However, as shown in Table 1(b) which shows the designed movable ranges of HRP-2P, several ranges of the joints of a humanoid robot should be extended or reduced because the kinematic configuration of a humanoid robot is different from that of a human in general, the dynamics of the robot is not identical with that of a human, and a humanoid robot is sometimes requested to perform the motions that a human can not. The ranges of the joints of HRP-2P have been designed by the simulations of various motions that may take place in the daily environments of humans.

4 Motion controller

4.1 Assumptions

The proposed controller has been investigated under the following assumptions.

- The getting up motion is executed on the flat and rigid floor.

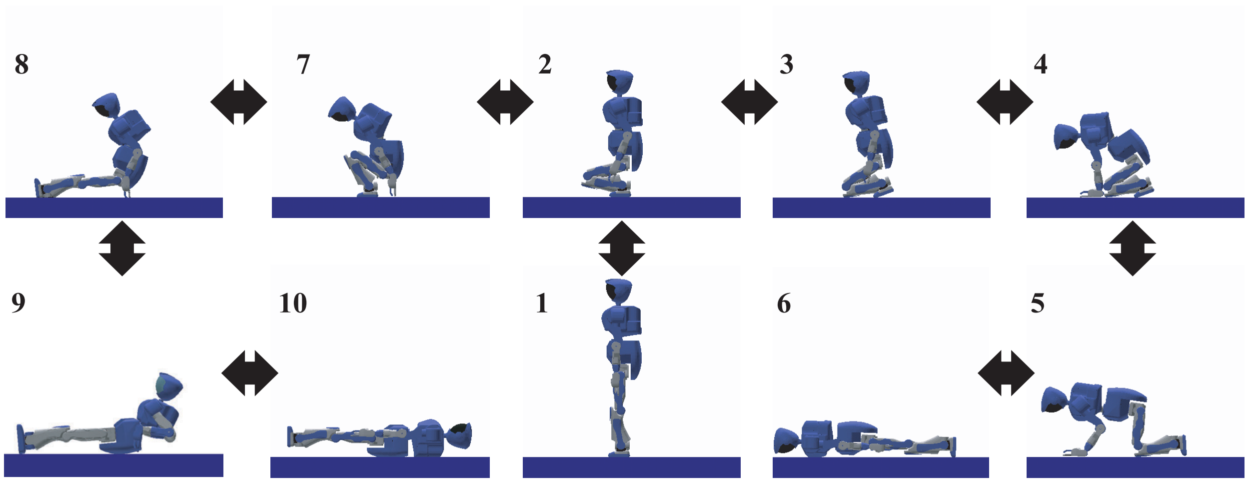

Figure 3: Contact states graph

Table 1: Movable ranges of joints of a standard human and humanoid robot HRP-2P

Joint			(a)Human	(b)HRP-2P
Head		R	-50 to 50	N.A.
		P	-50 to 60	-20 to 55
		Y	-70 to 70	-45 to 45
Right Arm	Shoulder	R	-90 to 0	-95 to 30
		P	-180 to 50	-180 to 60
		Y	-90 to 90	-90 to 90
	Elbow	P	-145 to 0	-135 to 0
		Y	-90 to 90	-90 to 90
	Wrist	R	-55 to 25	N.A.
		P	-70 to 90	-90 to 90
Right Hand		P	0 to 90	-16.5to 60
Waist		R	-50 to 50	N.A.
		P	-30 to 45	-5 to 60
		Y	-40 to 40	-45 to 45
Right Leg	Hip	R	-45 to 20	-35 to 20
		P	-125 to 15	-125 to 42
		Y	-45 to 45	-45 to 30
	Knee	P	0 to 130	0 to 150
	Ankle	R	-20 to 30	-20 to 35
		P	-20 to 45	-75 to 42

Unit:[deg], R: Roll axis, P: Pitch axis, Y: Yaw axis

- The initial state of the motion is the robot lying on the face or on the back.
- The coefficient of the friction between the robot and the floor is unknown. Therefore, the hands and feet should not be dragged during the motion.

4.2 Contact states graph

While executing a getting up motion, the contact state between the robot and the floor changes. In order to keep the balance of the robot, the relationship between the center of the mass of the robot and its support polygon must be controlled, but the support polygon changes according to the contact state drastically. Therefore, it is preferable to assign an appropriate controller to each contact state.

To this end, the continuous contact state is segmented into a set of the discrete contact states shown in Fig.3. The set can be represented by a graph, whose nodes are the discrete contact states and arcs the motions that make the transitions between the neighboring states. The graph is a undirectional graph, since the transitions are reversible.

The contact states are numbered as shown in Fig.3. The supporting parts of the body for the contact states are shown in Table 2. State 4 and State 5 have the identical supporting parts, but they are segmented since the shape of support polygons are different. In these states, fingers are not used as supporting parts since their structure is not so strong. Only in case that is highly required like in State 7, they are used as supporting parts.

4.3 Motion Controller for the transitions between the contact states

Most transitions between the discrete contact states can be realized by a static motion, during which the projection of the center of the mass onto the floor is

Table 2: Supporting Parts

No.	Support Parts	No.	Support Parts
1	sole	6	chest and toe
2	sole	7	sole and finger
3	knee and toe	8	heel and finger
4	wrist, knee and toe	9	hip and heel
5	wrist, knee and toe	10	back and hip

always within the support polygon. The only transition that needs a dynamic motion is that between State 2 and State 3, where the projection may not be in the support polygon during the dynamic motion. The reason why the transition requires the dynamic motion is that the knees and soles of the robot can not contact with the floor at the same time.

The static motions are executed as follows. (1) A statically stable motion is generated by controlling the position of the torso while keeping the supporting parts constrained by the floor. For instance, in case of the transition from State 2 to State 7, the projection is constrainted in the support polygon whose vertices are made of soles. Keeping the center of the mass on it, arms are stretched backward in order to enlarge the support polygon by adding fingers to supporting parts. (2) The generated motion is used as the desired trajectory of the joints of the robot, and a feedback control is applied to keep the robot follow the trajectory. During the feedback control, the orientation of the torso is estimated from the gyrometers and accelerometers on the torso through a Kalman filter. The orientation is used to find the relation between the center of the mass and the support polygon.

The dynamic motions are carried out as follows. Motions from State 3 to State 2 and from State 2 to State 3 are almost same. Therefore in the following, the detail of the motion from State 3 to State 2 is described.

The body of the robot must rotate around the toes to make the transition between State 3 and State 2. To this end, the hip pitch joints are moved to follow a sinusoidal wave

$$\theta_{hip} = A_{hip} \sin(\omega t) \tag{1}$$

for swinging the upper body backward. While the swinging motion, the inclination of the soles is found from the orientation of the torso, and the mode of the controller switches to another when the inclination reaches a specified angle.

The swinging motion makes the contact state from State 3 to State 2, but the robot may fall backward by the impact force from the landing of the soles and the inertial force. To prevent the falling, the new mode of the controller gives the robot a desired trajectory that is found by interpolating between the current posture and that of State 2, and the desired trajectory is modified to keep the balance of the robot by equations

$$\Delta P = P_d(t_i) - P(t_i), \tag{2}$$

$$\tilde{\theta}_{hip}(t_i) = k_1 \Delta P(t_i) + k_2 \tilde{\theta}_{hip}(t_{i-1}), \tag{3}$$

where $P_d(t_i)$ is the desired position of the zero moment point (ZMP) of the robot at time t_i, t_i means i-th sampling time, $P(t)$ is the actual position of ZMP that is computed from the outputs of the force sensors at the ankles, k_1 and k_2 are the gains of the feedback, and $\tilde{\theta}_{hip}$ is the compensation angle that is added to the hip pitch joints and subtracted from the ankle pitch joints.

5 Experimental results

The proposed controller has been implemented and was applied to HRP-2P. Figure 5 shows snapshots of a getting up motion of HRP-2P with the face downward, and Fig.6 those of the motion with the face upward. The snapshots are taken every five seconds, and each motion took about 30-40 seconds in total. In the experiments, $A_{hip} = 3.0$[deg], $k_1 = 0.06$ and $k_2 = 0.01$. Figure 4 shows $P(t)$ while transiting from State 3 to State 2. Horizontal dotted lines show foot size. A Horizontal line shows $P_d(t)$ that is set to the center of foot. At $t = 1.0$, the controller starts balance compensation. At $t = 2.0$, feet land on the ground and ZMP moves to heel by the effect of inertial force. After that ΔP decreases gradually.

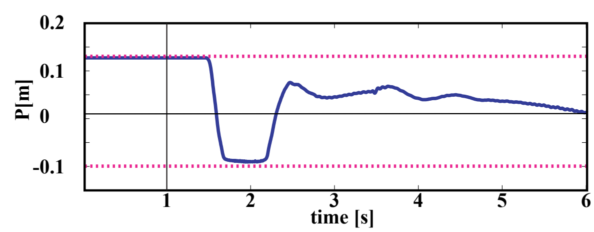

Figure 4: P while transiting from State 3 to State 2

As mentioned above, the motions are reversible. Figure 7 shows snapshots of a lying down motion with the face downward, and the motion with the face upward has been realized as well.

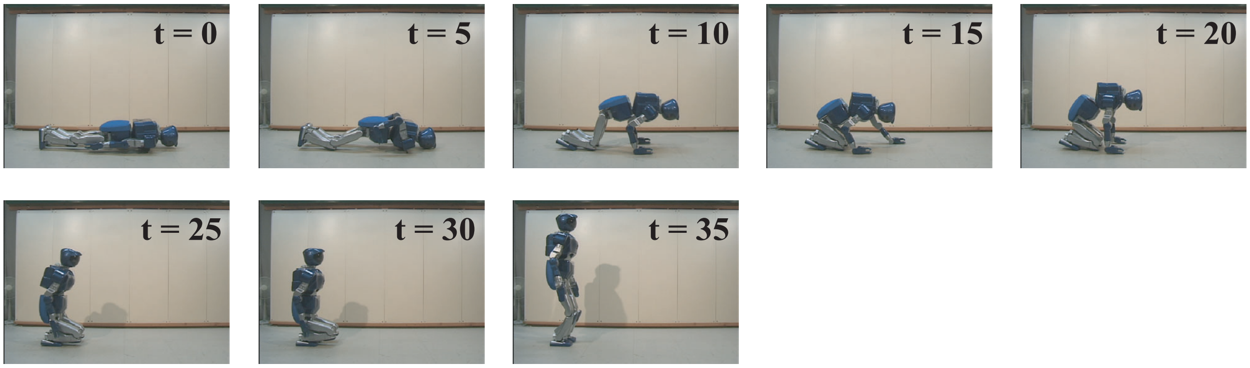

Figure 5: Getting up motion with the face downward

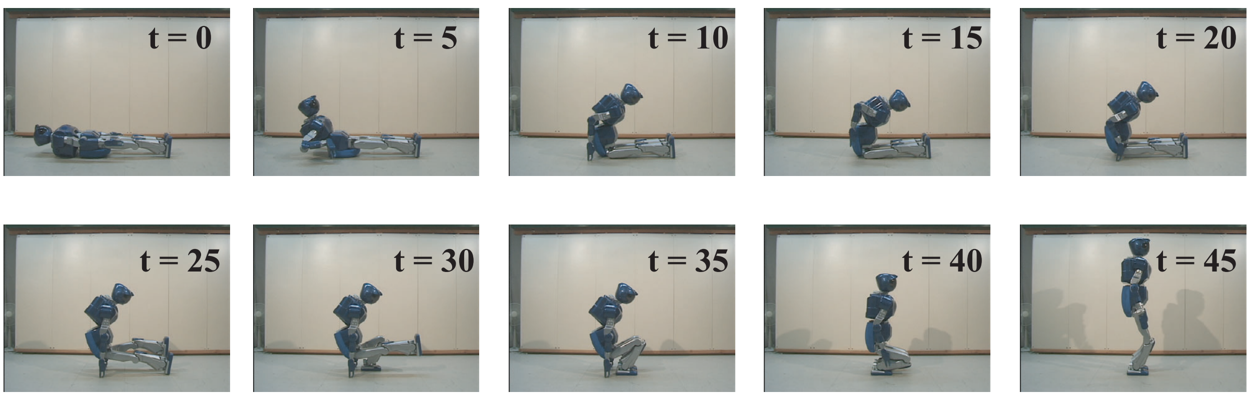

Figure 6: Getting up motion with the face upward

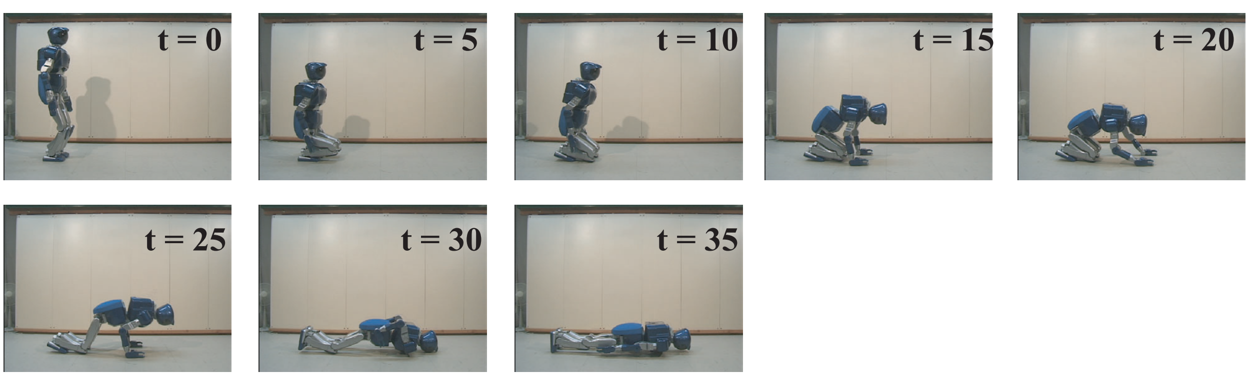

Figure 7: Lying motion with the face downward

6 Conclusions

This paper presented the first humanoid robot that has the same size as a human and that can lie down and get up with the face upward and downward, which has been realized the the following contributions.

- We have developed humanoid robot HRP-2P that is free from a large backpack, has a waist joint moving the upper half of the body forward and backward and joints with the wide movable ranges each of which covers the corresponding range of a human.
- We have proposed to segment the motions into the collection of the discrete contact states and represent them by the undirected graph. The controllers have been designed to realize the transitions between the contact states.

The significance of the results is enhanced by noting that a design principle of a humanoid robot can be switched from aiming for the robot that never tips over to realizing the robot that may tip over but can get up if the falling motion control is introduced as well[10]. The new design principle can relax the requirements for the controller of the biped walking as same as the fail-safe design principle can in other machinery.

We believe this is another important step to apply humanoid robot to real applications in the real world.

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