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Humanoid Robot HRP-4
- Humanoid Robotics Platform with Lightweight and Slim Body -

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Abstract — This paper presents the development of humanoid robotics platform – 4 (or HRP-4 for short). The high-density implementation used for HRP-4C, the cybernetic human developed by AIST, is also applied to HRP-4. HRP-4 has a total of 34 degrees of freedom, including 7 degrees of freedom for each arm to facilitate object handling and has a slim, lightweight body with a height of 151 [cm] and weight 39 [kg]. The software platform OpenRTM-aist and a Linux kernel with the RT-Preempt patch are used in the HRP-4 software system. Design concepts and mechanisms are presented with its basic specification in this paper.

1. Introduction

The future needs for robots are starting to change from factory automation to human friendly robot systems. Since work environments, houses, and machines are designed to suit human beings, the use of life-size humanoid robots is expected to help minimize the cost involved in modification of the work or home environment and reduce the overall cost for introducing the use of robots to society. Life-size humanoid robots are expected to be one of the next-generation robots. In recent years, private companies as well as universities and research institutes have been carrying out active research on such robots [1-16].

The most impressive humanoid robots are the HONDA humanoid robots. After the second prototype HONDA humanoid robot: P2 was revealed in 1996 [1], P3 [2] and ASIMO [3] debuted in 1997 and 2000 respectively. New ASIMO showed us its capability of running at 6 [km/h] on December 13, 2005 [4].

Under the collective experience of the Toyota Group, several types of Toyota Partner Robots were announced [5]. The humanoid robot playing a trumpet and four wheeled robots gave us a beautiful performance in the Toyota Group Pavilion at the EXPO 2005 in Aichi. On December 6, 2007, a humanoid robot playing a violin was revealed [6].

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Fig. 1. Humanoid robotics platform – 4 : HRP-4

Korea Advanced Institute of Science and Technology (KAIST) also developed several humanoid robots. The latest model: HUBO2 has a capability of running at 3.24 [km/h] [7].

LOLA [8], BHR-2 [9], iCub [10], Lucy [11], and REEM-B [12] are also prominent humanoid robots.

We have developed several humanoid robots, too. We released our humanoid robots: HRP-2 [13, 14], HRP-3 [15], and HRP-4C [16] in 2002, 2007, and 2009, respectively.

However, it is necessary to address many technological issues for the industrialization of life-size humanoid robots. One such issue is reduction of production cost. At present, the cost reduction issue has been successfully resolved for small humanoid robots (height: 50 [cm] or lesser), and these robots have been commercialized internationally. However, these robots have some problems including their size when they are used in serious research in a real environment that includes human activities. For this reason, low-price, life-size humanoid robots are in demand. In addition, low-power might be requested for the humanoid robots that must coexist with human beings in the future. It is also expected that the interoperability of software for humanoid robots would be improved by adopting interfaces conforming to international standards. As a R&D platform for working humanoid to research these issues, we developed HRP-4 shown in Fig. 1. In this paper, we describe the development of HRP-4.

2. Design Concepts of HRP-4's Hardware

We started the development of HRP-4 with the expectation that it will accelerate the R&D of next-generation robot systems necessary for the future robot industry, such as human-cooperative robots capable of operating under various environments. The design concepts of HRP-4 became as follows.

Design concepts:
A) Lightweight and slim body
B) Lower-price (than HRP-2)
C) Lower-power (than HRP-2)
D) Improve object manipulation
E) Expandability

The reasons why these design concepts were adopted and the method in which we realize them are as follows.

For operational reasons, and in order to make life-size humanoid robots easier and safer, the design concept A) was adopted. To realize this design concept, we planned to apply the high-density implementation used for HRP-4C [16], the cybernetic human developed by AIST, also for HRP-4. The design for a lightweight and slim body is explained in Section 4.

Since the price will be one of important factors in making a market for life-size humanoid robots in the future, the design concept B) was set as a goal at the beginning of HRP-4 development. To search for the possibility of reducing cost, we decided on the use of modularized units and common parts as shown in Section 5.

The design concept C) will also be one of important factors in making life-size humanoid robots that coexist with human in the future. Safety standard for robots used in personal care is being defined by the ISO (International Organization for Standardization) 10218-1:2006 at present [17, 18]. In the ISO 10218-1:2006 [19], it is written that a robot shall be designed to ensure either a maximum dynamic power of 80 [W] or a maximum static force of 150 [N] at the flange or TCP (determined by the risk assessment). Furthermore, according to Notification No.51(1983) announced by the Ministry of Health, Labour, and Welfare in Japan [20], the human and robot in operation must be separated by a wall when the robot uses a motor with an output of over-80 [W] in Japan. Although it is not sure that we shall act in accordance with these standards for designing life-size humanoid robots in future, we thought it is better to keep within the bounds of the latter standard at least. Another reason is that lower power is safer, so design concept C) was adopted. We tried to design HRP-4 using motors with an output of 80 [W] below as described in Section 6.

Since March 2003, we and General Robotix, Inc. have been supplying hardware and control software for the humanoid robot HRP-2, which are expected to be utilized for the existing research and development platform for working humanoid robots, for universities and research institutes. About 20 units have been put into use internationally so far. Eight years have already passed since the development and announcement of HRP-2, and the specification and performance of HRP-2, together with it's components are becoming unsuitable for some of the new research projects. For example, some customers request 7-DOF arm instead of original 6-DOF arm for research on manipulation. Due to this, the design concept D) was adopted and a 7-DOF arm was designed for HRP-4. The 3-DOF wrist joint is explained in Section 5. Some other customers wanted to add additional sensors that were necessary for their research projects. Yet another customer wanted to adopt a PC of their own selection, in which their own software such as visual recognition and voice recognition can run. Since the renewal cycle of current PCs is so fast, they want to change their PC frequently. The software system which enables to realize rich applications by simply combining existing software programs is also requested. This situation prompted us to adopt design concept E). The way in which we realized this demand is explained in Section 7.

3. Basic Specification of HRP-4

Based on the design concepts A) to E), we developed HRP-4. Table 1 shows its basic specification compared with that of HRP-2. HRP-4 is 1,514 [mm] high and the weight is 39 [kg] including batteries. Fig. 2 shows HRP series humanoid robots to show how slim HRP-4 is. Fig. 2 shows from the left, the front views of HRP-3, HRP-4C, body mechanism of HRP-4C, HRP-4, and side views of HRP-4 and HRP-2, while the right side of Fig. 2 shows the front view of HRP-2.

Fig. 3 shows the mechanical configuration of HRP-4. It is the same as HRP-2 apart from arms and hands. Due to design concept D), HRP-4 has 7-DOF arms with a 2-DOF hand while HRP-2 has 6-DOF arms with a 1-DOF hand. A 6-DOF leg is adopted to realize bipedal walking as with HRP-2. HRP-4 incorporates a 2-DOF waist and 2-DOF head making it 34 D.O.F. in total.

Table 1. Basic Specifications of HRP-2 and HRP-4

		HRP-2	HRP-4
Dimensions	Height	1,539 [mm]	1,514 [mm]
	Width	621 [mm]	458 [mm]
	Depth	355 [mm]	270 [mm]
Weight inc. batteries		58 [kg]	39 [kg]
D.O.F.		Total 30 D.O.F.	Total 34 D.O.F.
	Head	2 D.O.F.	2 D.O.F.
	Arm	2 Arms × 6 D.O.F.	2 Arms × 7 D.O.F.
	Hand	2 Hands × 1 D.O.F.	2 Hands × 2 D.O.F.
	Waist	2 D.O.F.	2 D.O.F.
	Leg	2 Legs × 6 D.O.F.	2 Legs × 6 D.O.F.
Control System		Centralized System	Distributed System
Batteries	Type	Ni-MH	
	Spec.	DC 48 [V], 14.8 [Ah]	DC 48 [V], 5.4 [Ah]

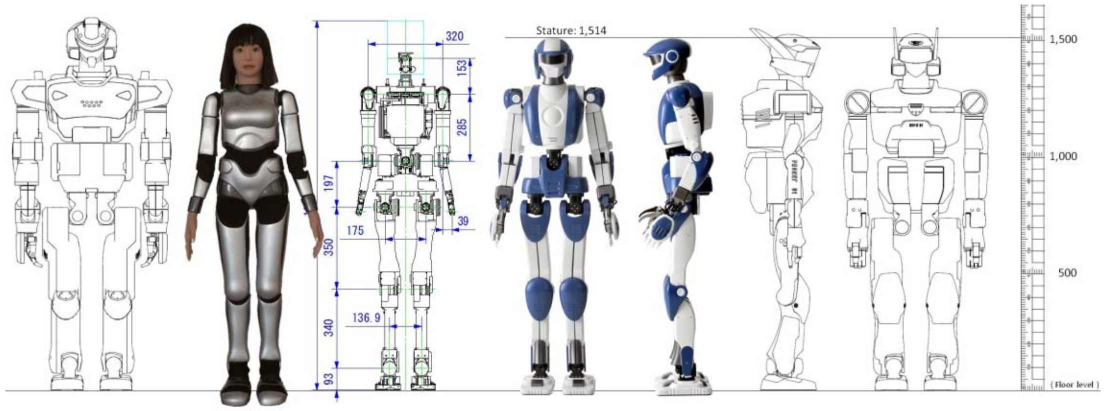


Fig. 2. Front views of HRP-3 (Left), HRP-4C (2nd Left), Body Mechanism of HRP-4C (3rd Left), HRP-4 (Middle), Side views of HRP-4C (3rd Right), HRP-2 (2nd Right), and Front view of HRP-2 (Right)

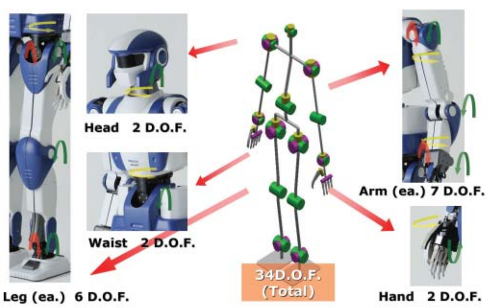
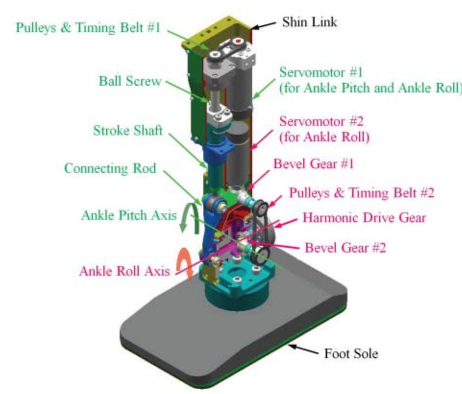
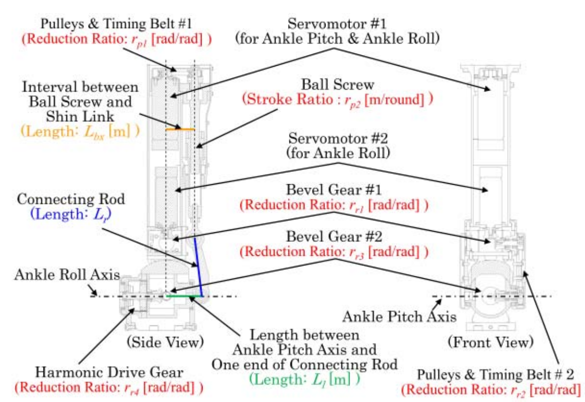


Fig. 3. D.O.F. Configuration of HRP-4



(a) Isometric drawing



(b) Sectioned drawing

Fig. 4. Ankle joint mechanism of HRP-4

We use Ni-MH (Nickel metal hydride) DC 48[V] batteries on the HRP-4. One reason why Li-ion (Lithium-ion) batteries are not used is because they must be handled with care. Li-ion batteries must be packaged with fail-safe circuits to avoid overheating or overcharging which can cause cell rupture. The other reason is that there is no huge difference between the volume of Li-ion batteries with fail-safe circuits and simple Ni-MH batteries.

4. Design for Lightweight and Slim Body

The body frame of HRP-4 is the almost the same as that of the HRP-4C as shown in Fig. 2. Arms and hands of HRP-4 are newly designed to realize design concept D). To design the lightweight and slim body of HRP-4, the high-density implementation used for HRP-4C is also applied to the HRP-4 and the same methodology used in the development of HRP-4C were used [16]. These are:

1) Miniaturizing the drive system
2) Employing the distributed control system
3) Employing the tiny and distributed motor drivers
4) Renewal of computer system.

To miniaturize the drive system, we requested a careful design of the weight of HRP-4. As the target weight of HRP-4C was set to around 40 [kg] [16], HRP-4 had the same target.

Although the miniaturization of the drive system allows for a slimmer body than HRP-2 and HRP-3, it alone was insufficient to realize a slim shin and a slim ankle joint. Therefore, we developed a new ankle joint mechanism for HRP-4C and HRP-4. Fig. 4 shows its new mechanism. The shin link and ankle joint of left leg are illustrated in Fig. 4, but the same parts are utilized for the right leg to realize design concept B).

As shown in Fig. 4, two servomotors (see servomotor #1 and servomotor #2 in Fig. 4) are mounted inside of shin link to drive ankle joint. They are arranged along the longer direction of shin link to make a slim shin.

To explain the principle of driving ankle joint, let us use the terms shown in Fig. 4. The output torque of "servomotor #1" is transmitted to the "ball screw" via "pulleys and timing belt #1". The "stroke shaft" then moves in the longer direction of shin link and pushes/pulls the "connecting rod". Since the "connecting rod" is connected to a link which enables to rotate around the "ankle pitch axis", the motion around the ankle pitch axis is achieved by driving "servomotor #1". The joint angle of ankle pitch: θ_p, can be written by using the rotational angle of servomotor #1: q_1, as (1), when we define the posture shown in Fig. 4(b) to be initial.

$$\theta_p = \frac{\pi}{2} - \cos^{-1}\left\{ \frac{ L_{bx}^2 + \left[\sqrt{L_r^2 - (L_l - L_{bx})^2} + r_{p2} r_{p1} \frac{q_1}{2\pi} \right]^2 + L_l^2 - L_r^2 }{ 2 \sqrt{ L_{bx}^2 + \left[\sqrt{L_r^2 - (L_l - L_{bx})^2} + r_{p2} r_{p1} \frac{q_1}{2\pi} \right]^2 } L_l } \right\} - \cos^{-1}\left\{ \frac{ \sqrt{L_r^2 - (L_l - L_{bx})^2} + r_{p2} r_{p1} \frac{q_1}{2\pi} }{ \sqrt{ L_{bx}^2 + \left[\sqrt{L_r^2 - (L_l - L_{bx})^2} + r_{p2} r_{p1} \frac{q_1}{2\pi} \right]^2 } } \right\} \quad (1)$$

Where,

L_{bx}: Interval between ball screw and shin link [m]

L_r: Length of connecting rod [m]

L_l: Length between ankle pitch axis and one end of connecting rod [m]

r_{p1}: Reduction ratio of pulleys and timing belt #1 [rad/rad]

r_{p2}: Stroke ratio of ball screw [m/round]

The output torque of "servomotor #2" is transmitted to the output side pulley of "pulleys and timing belt #2", via "bevel gear #1". The rotational axis of output side pulley of "pulleys and timing belt #2" is consistent with the "ankle pitch axis" and is also connected with the input side gear of "bevel gear #2". The rotational axis of output side gear of "bevel gear #2" is consistent with the "ankle roll axis" and is also connected with the input shaft of "harmonic drive gear" whose output part is connected with the foot. Since the relative position between the link which enables to rotate around the "ankle pitch axis" and the output side pulley of "pulleys and timing belt #2" is changed when the ankle pitch joint is driven, the motion around the ankle roll axis is achieved by driving both "servomotor #1" and "servomotor #2" to be exact. The joint angle of ankle roll: θ_r can be written by using the rotational angle of servomotor #1: q_1 and that of servomotor #2: q_2 as (2), when we define the posture shown in Fig. 4(b) to be initial.

$$\theta_r = r_{r4} r_{r3} r_{r2} r_{r1} q_2 + r_{r4} r_{r3} \theta_p \quad (2)$$

Where,

r_{r1}: Reduction ratio of bevel gear #1 [rad/rad]

r_{r2}: Reduction ratio of pulleys and timing belt #2 [rad/rad]

r_{r3}: Reduction ratio of bevel gear #2 [rad/rad]

r_{r4}: Reduction ratio of harmonic drive gear [rad/rad]

As shown in Fig. 4, the ankle joint mechanism of HRP-4 enables the ankle pitch axis to be orthogonal to the ankle roll axis realizing a compact 2-DOF ankle joint.

5. Design for Lower-price

We tried everything we could to reduce the overall cost of HRP-4. One of them was the adoption of modularized units and common parts as shown in Fig. 5.

Fig. 5 shows that the right arm is assembled using the same as the ones used for the left arm. It means that the 3D shape of the right arm and left arm are the same and they are not symmetrical with respect to the sagittal plane. However, we saw to it that they are close to plane symmetry by design. In the same way, the right shin is assembled using parts used for the left shin. The thighs also use the same parts for both thighs apart from only a main frame connection. The main frame connection for the right thigh and the left thigh are made by making different cuts to the same basic cast part. Since the difference between them is the cut surface for realizing "Y-shape" legs as shown in Fig. 2, it is no exaggeration to say that the right thigh is assembled by using the same parts as the ones used for assembling the left thigh.

The hip joint is modularized and it is used for right and left hip joints together with the waist joint. Since this modularized joint enables 3-axes joint, HRP-4 has a 3-DOF hip. However, when the waist joint of HRP-4 is assembled, the roll joint is replaced with a rigid joint to reduce cost. HRP-4 has a 2-DOF waist while the HRP-4C has a 3-DOF waist.

Similarly the modularized joint, which enables 3-axes motion, is employed for right and left wrist joints together with the neck joint. HRP-4 has 3-DOF wrists. To reduce cost, the roll motion of modularized joint is replaced with a rigid one at construction for the neck joint of HRP-4. Although HRP-4C has a 3-DOF neck, HRP-4 has a 2-DOF neck.

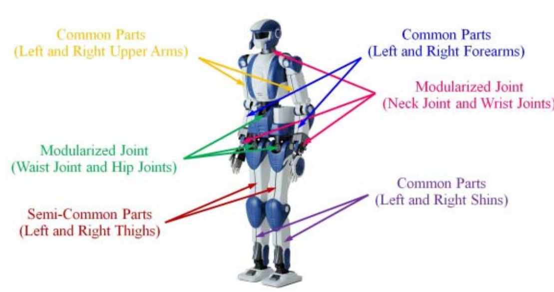


Fig. 5. Modularized units and common parts

Fig. 6 shows the mechanism of modularized joint employed for wrist joint. “Servomotor #1”, “harmonic drive gear #1”, and “pulleys and timing belt #1” which are utilized between them are adopted to drive the wrist yaw joint. By driving “servomotor #1”, the output shaft of “harmonic drive gear #1” is driven and the wrist yaw motion is generated. “Servomotor #2”, “harmonic drive gear #2”, and “Pulleys and timing belt #2” which are utilized between them are integrated to the output of “harmonic drive gear #1”. The output torque of “harmonic drive gear #2” is transmitted to a bracket to which “harmonic drive gear #3” is fixed via “parallel crank mechanism”. As a result, the bracket is driven by “servomotor #2” and the wrist pitch motion is generated. The structure of wrist roll joint is the same as that of wrist yaw joint. “Servomotor #3”, “harmonic drive gear #3”, and “pulleys and timing belt #3” which are utilized between them are adopted to drive the wrist roll joint. By driving “servomotor #3”, the output shaft of “harmonic drive gear #3” is driven and the wrist roll motion is generated. Both to reduce the cost and to maintain easily, the unit type harmonic drive gears are selected.

As shown in Fig. 6, the wrist joint mechanism of HRP-4 allows the wrist yaw, pitch, and roll axes to be orthogonal to each other, while at the same time realizing a compact 3-DOF wrist joint.

Other efforts we made to reduce cost were made by reviewing the machining process and simplifying the form of machined parts, streamlining the basic specification, and so on. As a result, the price of HRP-4 is 30 [%] cheaper than that of HRP-2.

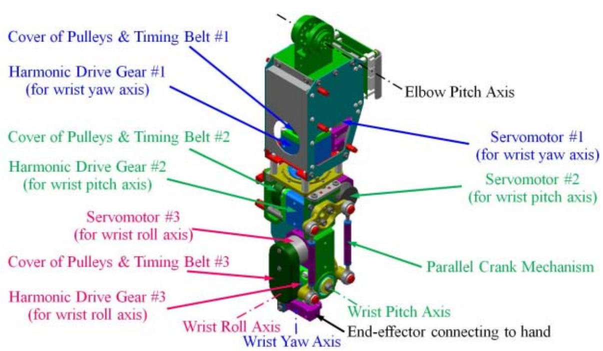


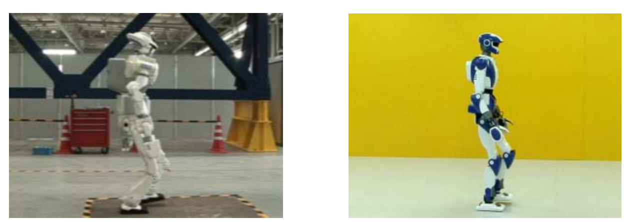
Fig. 6. Wrist joint mechanism of HRP-4

6. Design for Lower-power

As mentioned in Section 2, the design of life-size humanoid robots with lower-power will be one of the important factors in allowing them to coexist with human in the future. Its realization might be one of the challenging research topics. We tried to design HRP-4 using motors with less than 80 [W] output. In the rest of this section, we describe the design for lower-power with a focus on the knee joint that require more power.

One of important factors to realize life-size humanoid robots with low-power is reducing the weight of the robot. Since the kinetic energy is in proportion to the weight of robot, a robot with lighter weight consumes less energy. When we started the development of HRP-4, its target weight was set to around 40 [kg]. Since the weight of HRP-2 is 58[kg], about 30 [%] less power than HRP-2 might be sufficient to generate the same walking gait as HRP-2.

Another important factor to realize is the walking gait. From basic experiments in walking with a vertical waist motion [21], we foresaw that walking with a stretched knee will save energy. In out reference [22], it is written that the energy used for stretch-legged walking is about 83 [%] of bent-knee walking at step length 200 [mm]. It is also written that the energy of stretch-legged walking is about 56 [%] of bent-knee walking at step length 300 [mm]. When we generate a walking gait with constant waist height [23, 24], the knee needs the most power around the middle of single support phase with respect to a support leg (See Fig. 7(a)). As a result, walking with wider step length and constant waist height requires more energy. Table 2 shows the relation between knee joint torque and joint angle while standing when we consider a simple lumped mass model as



(a) Bent-knee (b) Knee roughly stretched

Fig. 7. Walking gait

Table 2. Relation between knee joint torque and knee joint angle of standing position using a simple lumped mass model

		Knee Joint Angle [deg.]									
		90	80	70	60	50	40	30	20	10	0
Knee Joint Torque [%]	Normalization #1	100.0	90.9	81.1	70.7	59.8	48.4	36.6	24.6	12.3	0.0
	Normalization #2	110.0	100.0	89.2	77.8	65.7	53.2	40.3	27.0	13.6	0.0
	Normalization #3	123.3	112.1	100.0	87.2	73.7	59.6	45.1	30.3	15.2	0.0
	Normalization #4	141.4	128.6	114.7	100.0	84.5	68.4	51.8	34.7	17.4	0.0
	Normalization #5	167.3	152.1	135.7	118.3	100.0	80.9	61.2	41.1	20.6	0.0
	Normalization #6	206.7	187.9	167.7	146.2	123.6	100.0	75.7	50.8	25.5	0.0
	Normalization #7	273.2	248.4	221.6	193.2	163.3	132.1	100.0	67.1	33.7	0.0
	Normalization #8	407.2	370.2	330.3	287.9	243.4	197.0	149.0	100.0	50.2	0.0
	Normalization #9	811.3	737.5	658.1	573.7	484.9	392.4	297.0	199.2	100.0	0.0

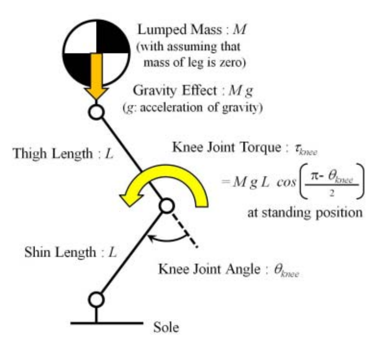


Fig. 8. Lumped mass model

shown in Fig. 8. Namely, to obtain Table 2, we assume that leg has no mass, the lumped mass is located in the body. Knee joint torque is calculated by

$$\tau_{knee} = M\, g\, L \cos\{ (\pi - \theta_{knee}) / 2 \} , \quad (3)$$

where

τ_{knee} : Knee joint torque [Nm]
M : Lumped mass [kg]
g : Acceleration of gravity [m/sec^2]
L: Length of thigh (assume length of shin is also L.)
θ_{knee} : Knee joint angle [rad] .

In Table 2, normalized torque is listed on each line. For instance, "normalization #5 in Table 2" shows that the knee joint torques at θ_{knee} = 40 [deg.], θ_{knee} = 30 [deg.], and θ_{knee} = 20 [deg.] are about 81 [%], 61 [%], and 41 [%] of that at θ_{knee} = 50 [deg.] respectively. Looking at Table 2, it is apparent that motions with straight knee require lower knee joint torque.

Both by reducing the weight of the robot and walking with stretched-knees, life-size humanoid robots with lower-power become much closer to realization. When we developed HRP-2L [25] which was the leg module for evaluating the hardware before developing HRP-2, a 150 [W] motor was adopted for the knee joint. Assuming a 30 [%] lighter robot and new walk pattern which requires 70 [%] of previous knee joint torque for bent-knee motion, power can be halved (49 [%] = 0.7 × 0.7). This means that life-size humanoid robots using motors with an output of 80 [W] below are possible.

To confirm this, we therefore designed HRP-4 taking care of its weight and have developed our new walk pattern generator that enables stretched-knee walking. Our new pattern generator is in progress and is improved from our previous ones [26, 27]. Fig. 7 (b) shows the walking gait which is generated by our current walk pattern generator.

7. Design for Expandability

Fig. 9 shows the electrical system of HRP-4. As shown in Fig. 9, HRP-4 has a distributed control system like HRP-4C, while HRP-2 has a centralized control system. Communication between a CPU board and motor drivers is realized using an internal network based on CAN (Controller Area Network). Since the I/O ports of HRP-2 are almost all occupied, there is little possibility of expansion in HRP-2. HRP-4 has some possibilities of expandability as explained below.

A PCI-104 form factor [28] SBC (Single Board Computer) with Intel® Pentium M® 1.6 [GHz] (90.17 [mm] × 95.89 [mm] board outline) is selected for the CPU board for controlling whole body motion and is mounted inside of the body. One of reasons why the PCI-104 SBC was selected is its scalability. We can easily stack up peripheral boards on the CPU board and expanding the I/O system. The other reason is that it is too hard to install other types of form

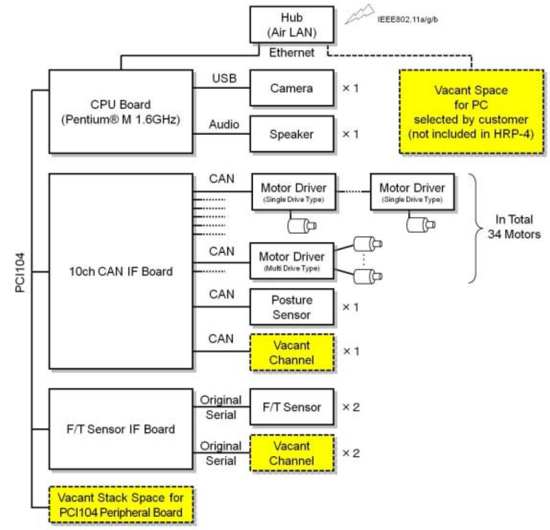


Fig. 9. Electrical System of HRP-4

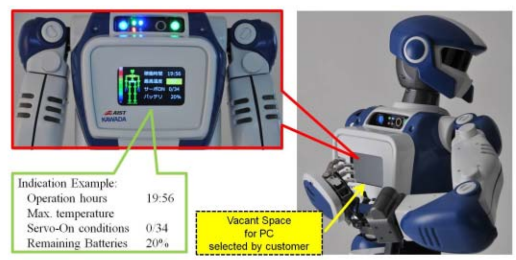


Fig. 10. Example of application of optional PC mounted in the back of HRP-4

factor with similar scalability, such as ISA, PCI, Compact PCI, and PICMG, inside the body.

As PCI bus restricts the number of stackable peripheral boards and we need to to control a lot of motors and sensors, we developed a couple of new peripheral boards during development of HRP-4C. One is "10ch CAN IF Board" communicating with CAN devices such as distributed motor driver and a posture sensor. The other is "F/T Sensor IF Board" controlling F/T sensors. Since these two are stacked up in the computer system to control the whole body, there is space for another PCI form factor peripheral board.

Since CAN devices can be daisy chained to each other serially, the installation of additional CAN devices is comparatively easy, though we should pay attention to the number of devices connected to maintain communication speed.

We also prepared extra space in the back of HRP-4 as shown in Fig. 10. At the press-release of the HRP-4 on September 15, 2010 [29], we installed a pocket PC (Size: 154 [mm] × 84 [mm] × 24.4 [mm], Processor: Intel Atom 1.33 [GHz]) [30] into that space. This pocket PC was utilized for visual recognition, voice recognition, and status monitoring. Fig. 10 shows the back of HRP-4 and PC screen indicating the status of HRP-4 such as operation hours and remaining batteries.

Fig. 11 shows the software system for HRP-4. To realize rich applications by simply combining existing software programs, we adopt the middleware platform OpenRTM-aist [31] and a Linux kernel with the RT-Preempt patch for the HRP-4 software system. The reason we adopt the Linux kernel with the RT-Preempt patch is to ensure that the OS is suited for hard real-time processing. Thus, the development of real-time software programs utilizing the standard POSIX API and the effective use of multi-core processors, which have gained popularity in recent years, are possible. OpenRTM-aist, which is the implementation of RT Middleware, a software technology that enables the combination of various functional robotic components via a communication network, is adopted as the middleware of the system. The motion control software comprises of a group of RT components incorporated with the motion control technologies developed for the HRP Series as the core logic. This enables efficient development of software by utilizing the development tools supporting RT Middleware and the existing RT components. Namely, the software system shown in Fig. 11 brings further expandability to software development.

8. Experiments

At the press-release of the HRP-4 on September 15, 2010 [29], we gave a demonstration [32, 33]. Figs. 12 and 13 show a snapshot of it walking and turning respectively [32]. This walking motion and turning motion are generated by our new walk pattern generator which is in progress and is improved from our previous ones [26, 27] and are stabilized by feedback controller [33-35]. Looking at these figures, it is obvious that the knee of single support leg is stretched. The walking step length is 350 [mm/step] and its step cycle is 0.8 [sec/step]. Fig. 12 tells us that a stable walk (1.575 [km/h]) is realized. It is observed that a 180 [deg.] turn can be realized by 4 steps (0.8 [sec/step]) from Fig. 13. The successful performance at the press-release indicates the effectiveness of the development.

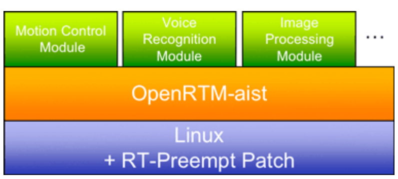


Fig. 11. Software system for HRP-4

9. Conclusions

This paper presented the development of HRP-4. The high-density implementation used for HRP-4C was applied to HRP-4. Designing with careful weight adjustment and miniaturizing the drive system, life-size humanoid robots with a slim body using motors with an output of 80 [W] below has been realized. Our new pattern generator which is in progress also contributed to the successful development of HRP-4.

Future work includes further improvement of HRP-4, which reflecting user feedback and requests. Although stable walking can be realized using HRP-4 with our previous pattern generator which generates a gait with constant waist height [23, 24], its walking step length is restricted. The improvement of our new pattern generator towards stretched-knee walking, which enables walking with a wider step length, is also our future work. We are expecting HRP-4 will accelerate the R&D of next-generation robot systems necessary for the robot industry of the future, which is expected to be human-cooperative and capable of operating under various environments.

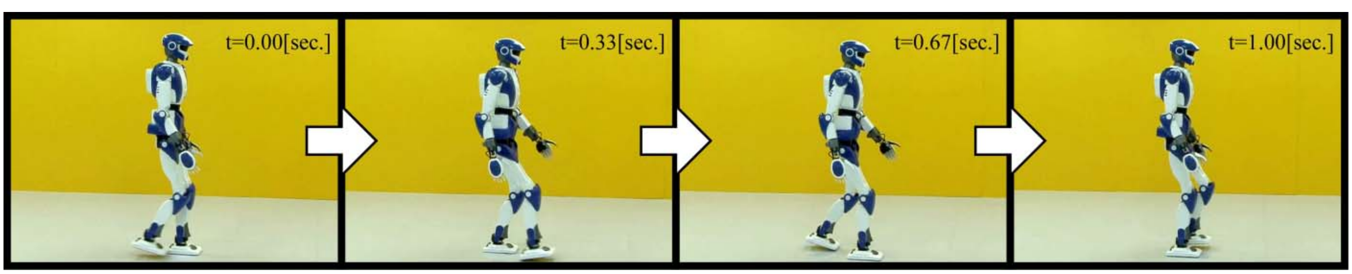


Fig. 12. Walking at the press-release of HRP-4 (Walking speed: 1.575 [km/h])

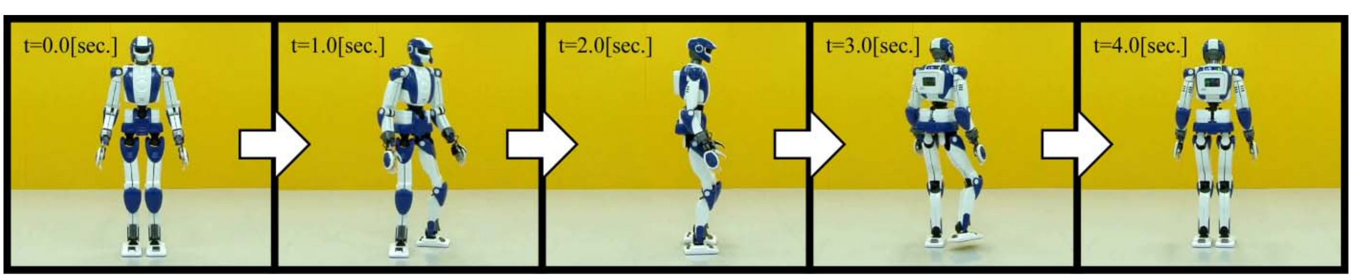


Fig. 13. Turning at the press-release of HRP-4

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References

[1] K. Hirai, "Current and Future Perspective of Honda Humanoid Robot," Proc. IEEE/RSJ Int. Conference on Intelligent Robots and Systems, pp. 500-508, 1997.

[2] K. Hirai, M. Hirose, Y. Haikawa, and T. Takenaka, "The Development of Honda Humanoid Robot," Proc. IEEE Int. Conference on Robotics and Automation, pp. 1321-1326, 1998.

[3] M. Hirose, Y. Haikawa, T. Takenaka, and K, Hirai, "Development of Humanoid Robot ASIMO," Proc. IEEE/RSJ Int. Conference on Intelligent Robots and Systems, Workshop2 (Oct. 29, 2001), 2001.

[4] Honda Motor Co., Ltd., "Honda new ASIMO," Press release information, http://www.honda.co.jp/news/2005/c051213-asimo.html, 2005.

[5] S. Takagi, "Toyota Partner Robots," Journal of the Robotics Society of Japan, Vol. 24, No. 2, pp. 208-210, 2006 (in Japanese).

[6] Toyota Motor Corporation., "Development Outline of Toyota Partner Robot," Press release information, http://www.toyota.co.jp/jp/news/07/Dec/nt07_076.html, 2007.

[7] B. K. Cho, S. S. Park and J. H. Oh, "Controllers for Running in the Humanoid Robot, HUBO," Proc. IEEE-RAS Int. Conference on Humanoid Robots, pp. 385-390, 2009.

[8] S. Lohmeier, T. Buschmann, and H. Ulbrich, "Humanoid Robot LOLA," Proc. IEEE Int. Conference on Robotics and Automation, pp. 775-780, 2009.

[9] Z. Peng Y. Fu, Z. Tang, Q. Huang, and T. Xiao, "Online Walking Pattern Generation and System Software of Humanoid BHR-2" Proc. IEEE/RSJ Int. Conference on Intelligent Robots and Systems, pp. 5471-5476, 2006.

[10] G. Metta, G. Sandini, D. Vernon, L. Natale, and F. Nori, "The iCub humanoid robot: an open platform for research in embodied cognition" Performance Metrics for Intelligent Systems Workshop, http://www.robotcub.org/misc/papers/08_Metta_Sandini_Vernon_etal.pdf, 2008.

[11] B. Vanderborght, B. Vorrelst, R. V. Ham, M. V. Damme, and D. Lefeber, "A Pneumatic Biped: Experimental Walking Results and Compliance Adaptation Experiments," Proc. IEEE-RAS Int. Conference on Humanoid Robots, pp. 44-49, 2005.

[12] Pal Technology Robotics, http://www.pal-robotics.com/

[13] K. Kaneko, F. Kanehiro, S. Kajita, H. Hirukawa, T. Kawasaki, M. Hirata, K. Akachi, and T. Isozumi, "Humanoid Robot HRP-2," Proc. IEEE Int. Conference on Robotics and Automation, pp. 1083-1090, 2004.

[14] K. Kaneko, F. Kanehiro, S. Kajita, K. Fujiwara, K. Harada, K. Yokoi, and H. Hirukawa, "Humanoid Robot HRP-2 Promet," Video Proc. IEEE Int. Conference on Robotics and Automation, VideoA, 2004.

[15] K. Kaneko, K. Harada, F. Kanehiro, G. Miyamori, and K. Akachi, "Humanoid Robot HRP-3," Proc. IEEE/RSJ Int. Conference on Intelligent Robots and Systems, pp. 2471-2478, 2008.

[16] K. Kaneko, F. Kanehiro, M. Morisawa, K. Miura, S. Nakaoka, and S. Kajita, "Cybernetic Human HRP-4C," Proc. IEEE-RAS Int. Conference on Humanoid Robots, pp. 7-14, 2009.

[17] Y. Yamada, "Trend of International Safety Standard for Robots in Personal Care," Data of 1st meeting for considering on Guidelines of Ensuring Safety for Next-Generation Robot, http://www.meti.go.jp/policy/robotto/saftygl/gl1_5-2.pdf, 2006 (in Japanese).

[18] Ministry of Economy, Trade and Industry of Japan, "Guidelines of Ensuring Safety for Next-Generation Robot," Press data, http://www.meti.go.jp/press/20070709003/02_guideline.pdf, 2007 (in Japanese).

[19] International Organization for Standardization, "Robots for industrial environments -- Safety requirements -- Part 1: Robot," http://www.iso.org/iso/catalogue_detail.htm?csnumber=36322, 2006.

[20] Ministry of Labor of Japan, "Manipulator decided by Minister of Labor of Japan based on article 36-31 of ordinance on labor safety and hygiene," Notification No. 51, July/01/1983 (in Japanese).

[21] M. Morisawa, S. Kajita, K. Kaneko, K. Harada, F. Kanehiro, K. Fujiwara, and H. Hirukawa, "Pattern Generation of Biped Walking Constrained on Parametric Surface," Proc. IEEE/RSJ Int. Conference on Intelligent Robots and Systems, pp. 2416-2421, 2005.

[22] M. S. Kim, I. Kim, S. Park, and J. H. Oh, "Realization of Stretch-legged Walking of the Humanoid Robot," Proc. IEEE-RAS Int. Conference on Humanoid Robots, pp. 118-124, 2008.

[23] S. Kajita, F. Kanehiro, K. Kaneko, K. Fujiwara, K. Yokoi, and H. Hirukawa, "A Realtime Pattern Generator for Biped Walking," Proc. IEEE Int. Conference on Robotics and Automation, pp. 31-37, 2002.

[24] S. Kajita, F. Kanehiro, K. Kaneko, K. Fujiwara, K. Harada, K. Yokoi, and H. Hirukawa, "Resolved Momentum Control: Humanoid Motion Planning based on the Linear and Angular Momentum," Proc. IEEE/RSJ Int. Conference on Intelligent Robots and Systems, pp. 1644-1650, 2003.

[25] K. Kaneko, S. Kajita, F. Kanehiro, K. Yokoi, K. Fujiwara, H. Hirukawa, T. Kawasaki, M. Hirata, and T. Isozumi, "Design of Advanced leg Module for Humanoid Robotics Project of METI," Proc. IEEE Int. Conference on Robotics and Automation, pp. 38-45, 2002.

[26] M. Morisawa, K. Harada, S. Kajita, K. Kaneko, F. Kanehiro, K. Fujiwara, S. Nakaoka, and H. Hirukawa, "A Bipedal Pattern Generation Allowing Immediate modification of Foot Placement in real-time," Proc. IEEE-RAS Int. Conference on Humanoid Robots, pp. 581-586, 2006.

[27] F. Kanehiro, W. Suleiman, K. Miura, M. Morisawa, and E. Yoshida, "Feasible Pattern Generation Method for Humanoid Robots," Proc. IEEE-RAS Int. Conference on Humanoid Robots, pp. 542-548, 2009.

[28] PC/104 Embedded Consortium, "PCI-104 Specification Version 1.0," http://www.winsystems.com/specs/PCI-104Spec_v1_0.pdf, 2003.

[29] AIST, "Development of HRP-4, a Research and Development Platform for Working Humanoid Robots - Supply to external research organizations from January 2011 -," Press release information, http://www.aist.go.jp/aist_e/latest_research/2010/20101108/20101108.html, 2010.

[30] Yukyung Technologies Corporation, "viliv S5," http://www.myviliv.com/eng/product/s5.asp

[31] N. Ando, T. Suehiro, K. Kitagaki, T. Kotoku, and W. K, Yoon, "RT-Middleware: Distributed Component Middleware for RT (Robot Technology)," Proc. IEEE/RSJ Int. Conference on Intelligent Robots and Systems, pp. 3555-3560, 2005.

[32] AIST, "Walking, Warm-up Exercises, and so on, by HRP-4," AIST Channel in You Tube, http://www.youtube.com/user/aistchannel#p/u/36/tcDyZ89TRAA, 2009.

[33] K. Kaneko, K. Yokoi, F. Kanehiro, S. Kajita, K. Fujiwara, and H. Hirukawa, "Walking Control Device for Bipedal Robot," Japanese Patent #3646169 (application date: 07/May/2002), 2005 (in Japanese).

[34] K. Kaneko, F. Kanehiro, K. Fujiwara, K. Harada, K. Yokoi, S. Kajita, and H. Hirukawa, "Operational Force Generation Device," Japanese Patent #4113948 (application date: 17/July/2003), 2008 (in Japanese).

[35] K. Kaneko, F. Kanehiro, S. Kajita, M. Morisawa, K. Fujiwara, K. Harada, and H. Hirukawa, "Slip Observer for Walking on a Low Friction Floor," Proc. IEEE/RSJ Int. Conference on Intelligent Robots and Systems, pp. 1457-1463, 2005.