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# Humanoid Robot HRP-3

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***Abstrac*t** — In this paper, the development of humanoid robot HRP-3 is presented. HRP-3, which stands for Humanoid Robotics Platform–3, is a human-size humanoid robot developed as the succeeding model of HRP-2. One of features of HRP-3 is that its main mechanical and structural components are designed to prevent the penetration of dust or spray. Another is that its wrist and hand are newly designed to improve manipulation. Software for a humanoid robot in a real environment is also improved. We also include information on mechanical features of HRP-3 and together with the newly developed hand. Also included are the technologies implemented in HRP-3 prototype. Electrical features and some experimental results using HRP-3 are also presented.

## 1. Introduction

Humanoid robot, which can walk by two legs and perform skilful tasks using both arms with hands, could be considered as one of the ultimate robots, with applications on only on Earth but also in Space [1]. Currently, research on humanoid robots is one of the most exciting topics. It is no exaggeration to say that the great success of HONDA humanoid robot triggered the world's research on humanoid robots [2-4]. Since the second prototype HONDA humanoid robot: P2, was revealed in 1996, many biped humanoid robots have been developed [5-9].

LOLA is an anthropomorphic autonomous biped robot and its development is in progress at the Technical University of Munich to realize fast and human-like walking motion [5]. The height of LOLA will be 1800 [mm] with 22 D.O.F. The distributed joint control and sensor data processing are realized by Ethernet-based real-time communication system: SERCOS-III.

HUBO is humanoid robot developed by Korea Advanced Institute of Science and Technology (KAIST). The height of HUBO is 1250 [mm] and weight is 55 [kg] including batteries [6]. Its walking speed is up to 1.25 [km/h]. HUBO has a total of 41 D.O.F. A distributed control architecture using CAN (Controller Area Network) is adopted.

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Figure 1. Humanoid Robot HRP-3

The collective experience of the Toyota Group is focused on its development of Toyota Partner Robots [7]. The music Playing Robots, which consist of 5 models (one 2-legged walking model and four wheeled rolling models), gave a beautiful performance in the Toyota Group Pavilion at the EXPO 2005 in Aichi. The 2-legged walking model, which is 1450 [mm] high and weighs 40 [kg] including batteries with 31 D.O.F., has an artificial lip with the similar structure as humans and plays a trumpet.

The most impressive humanoid robots should be HONDA humanoid robots. In 2000, downsizing P2 [2] and P3 [3], ASIMO (height 1200 [mm], width 450 [mm], weight 52 [kg], with 26 D.O.F.) debuted with a new walking technology (i-WALK) [4]. The newest impression is that the new ASIMO, which is 1300 [mm] high, 450 [mm] in width, and weighs 54 [kg] with 34 D.O.F., debuted with the capability of running at 6 [km/h] on December 13, 2005. It is no exaggeration to say that the great success of the HONDA humanoid robot triggered the world's research on humanoid robots.

The more humanoid robots, which can walk and go up/down stairs, are developed, the more humanoid robots are expected to perform actual tasks in the human living environment. For research and development of humanoid robots performing application tasks, the Ministry of Economy, Trade and Industry (METI) of Japan had run Humanoid Robotics Project (HRP for short) from 1998FY to 2002FY [10]. In the HRP project, we developed HRP-2 [8]. However, HRP-2 wasn't designed to be operated outdoors as with other humanoid robots. In the near future, key technologies of humanoid robot working outdoors are definitely required. To establish them, we started to develop HRP-3, which is a human-size humanoid robot developed as the succeeding model of HRP-2.

This paper presents the development of HRP-3. Several new developed technologies, which are not only hardware but also software, are implemented into HRP-3. In this paper, mechanical features of HRP-3 and new developed hand are presented, introducing technologies implemented in HRP-3 prototype: HRP-3P [11]. Electrical features and some experimental results using HRP-3 are also presented.

## 2. Principal Specifications

### 2-1. Design concepts

The design concepts of HRP-3 are as follows.

A) Build upon the capabilities of HRP-2
B) Improve object manipulation
C) Dust proof and splash proof design

Since HRP-3 is the succeeding model of HRP-2, the design concept A) is obvious. Since tasks carried out by HRP-2 are limited, the design concept B) is incorporated into the design plan. In Section 3, we explain the 3-fingered hand newly developed to expand the range of tasks capable by HRP-3. The design concept C) is the most important, to establish the application of humanoid robots working outdoors. In Section 4, the mechanisms preventing the penetration of dust or moisture are explained in detail.

Table 1. Principal Specifications of HRP-3

| | | |
|---|---|---|
| Dimensions | Height | 1,606 [mm] |
| | Width | 693 [mm] |
| | Depth | 410 [mm] |
| Weight inc. batteries | | 68 [kg] |
| D.O.F. | | Total 42 D.O.F. |
| | Head | 2 D.O.F. |
| | Arm | 2 Arms × 7 D.O.F. |
| | Hand | 2 Hands × 6 D.O.F. |
| | Waist | 2 D.O.F. |
| | Leg | 2 Legs × 6 D.O.F. |
| Operational Time | | 120 [min] |
| Feature | | Dust/Splash-proof |

Figure 1 shows HRP-3 which was developed based on design concepts A) to C). Table 1 shows the principal specifications of HRP-3. As shown in Table 1, HRP-3 is 1606 [mm] high and weight is 68 [kg] including batteries. Since HRP-2 is 1539 [mm] high and weighs 58 [kg] including batteries [8], HRP-3 has grown a little larger than HRP-2. This growth is due to realizing design concepts B) and C). For example, HRP-3 has a total of 42 D.O.F., while HRP-2 has a total of 30 D.O.F. Servo motors and harmonic drive gears are selected to construct the drive system similar to the HRP-2.

### 2-2. Configuration

Figure 2 shows the mechanical configuration of HRP-3. As shown in Figure 2, the mechanical configuration of HRP-3 is the almost same as that of HRP-2, while the number of driven joints is slightly increased. HRP-3 inherits unique structural components from HRP-2 as explained below.

One of unique structural components is that the hip joint of HRP-3 has a cantilever type structure. The reason for this is that the cantilever type structure enables to have less collision between the inside thigh-links. Using this structure, the robot can walk on a narrow path crossing its legs, while putting on foot in front of the other [9].

The other is that HRP-3 has a waist joint with 2 D.O.F. likewise to HRP-2, since the waist joint also brings several advantages. The waist joint with 2 D.O.F. (pitch axis and yaw axis) enabled HRP-2 to get up itself [12]. The extra degrees of freedom in the upper body would also make it possible to smoother the gait. HRP-2 was also able to crawl on hands and knees using the waist joint [9]. The moment generated around the yaw axis of bipedal robot can be suppressed by using waist motion. This compensation is especially important for high-speed walking. 2.5 [km/h] walk was successfully achieved by HRP-2 with using waist motion [8, 9]. Furthermore, the waist joint extends the working space of arms.

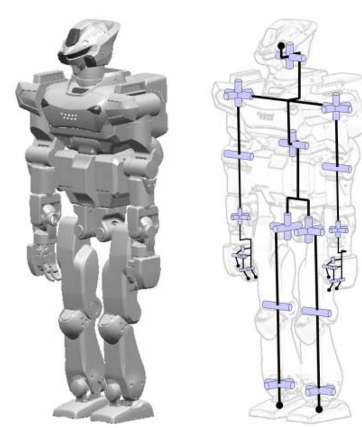


Figure 2. Configuration of HRP-3

The wrist and hand of HRP-3 are redesigned from those of HRP-2 to achieve design concept B). HRP-3 has 7 D.O.F. in each arm redundancy, while there were only 6 D.O.F. for HRP-2. The design of the new hand is explained in the next section.

## 3. Three-fingered hand

To achieve design concept B), the wrist and the hand of HRP-3 are newly developed.

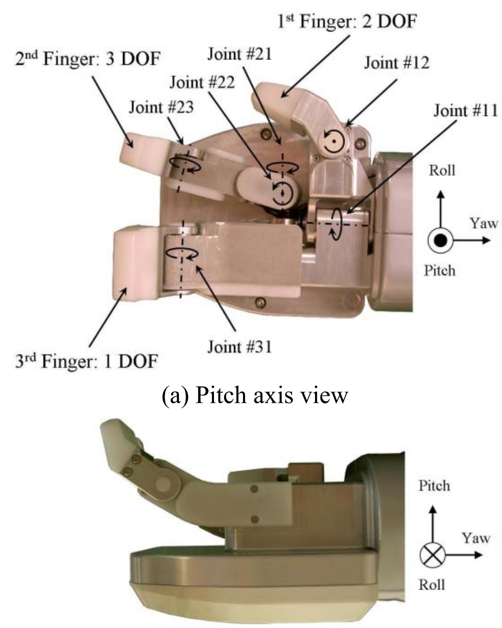
When we experimented on manipulation using 6 D.O.F. arm [ 3 D.O.F. Shoulder, 1 D.O.F. Elbow, 2 D.O.F. Wrist ] of HRP-2, the upper-arm link frequently collided with the chest cover, even with an extended movable range 6 D.O.F. arm compared with a standard human one. To overcome this issue, we design HRP-3 to have 7 D.O.F. for each arm. As shown in Figure 2, the arm configuration of HRP-3 is designed by adding one driven joint to the wrist configuration of HRP-2. As with the majority of industrial-arms with 7 D.O.F., HRP-3 has a 3 D.O.F. shoulder, a 1 D.O.F. elbow, and a 3 D.O.F. wrist.

The hand design of HRP-3 was restarted from ground up by reflecting on our previous work as follows. In HRP-2, we adopted a 1 D.O.F. hand. The reason is that the main application task by HRP-2 was grasping a panel. It was designed as a gripper. As a matter of course, application tasks performed by HRP-2 are discouragingly limited. Secondly a mitten type of hand, which has 3 D.O.F., was designed and was adopted into HRP-3P [11]. The first finger imitating a thumb has 1 D.O.F., while second finger, which is imitatively constructed by bundling up index, middle, ring, and little fingers, has 2 D.O.F. These fingers of HRP-3P can be wrapped around grasping objects. The second finger is also utilized for grasping objects powerfully. Although the capability of grasping objects by HRP-3P is a little improved over the HRP-2, application tasks performed by HRP-3P are still limited. It is also difficult for HRP-2 and HRP-3P to do simple tasks such as operating a push type switch and pulling the trigger of electrical driver. Ultimately a multi-fingered hand is required to perform human tasks as well as a human [13-15]. To achieve this requirement, we also developed a multi-fingered hand, which can be attached to life-size humanoid robots [16]. Our developed multi-fingered hand has 4 fingers with 17 joints, which consist of 13 active joints and 4 linked joints. As expected, our hand is applicable both for grasping and manipulating objects on a prototype level. However, it is still premature to adopt our developed multi-fingered hand into HRP-3 as a product model. In addition, it is necessary for the hand of HRP-3 to have splash-proof and dust-proof functions. It was too hard for us to realize a life-size and multi-fingered hand with splash-proof and dust-proof functions while confirming to the schedule of developing HRP-3. The development cost of multi-fingered hands is another issue.

According to our previous experiences and our above opinion, we designed the new hand for HRP-3. The following are design concepts for designing the hand of HRP-3.

D) Gripper like functionality of the HRP-2 hand
E) Grasping functionality of the HRP-3P hand
F) Capability of wrapping fingers around object like the HRP-3P hand
G) Capability of achieving simple tasks using one finger, such as operating a push type switch and pulling the trigger of electrical driver

The hand of HRP-3 was designed based on design concepts D) to G) together with design concepts B) and C). Figure 3 shows the developed hand of HRP-3, which has three fingers and a total of 6 D.O.F.




(a) Pitch axis view

(b) Roll axis view

Figure 3. Three-fingered hand with 6 D.O.F.

The first finger imitating a thumb has 2 D.O.F. One joint is arranged at the base and is utilized for facing the thumb forwards second finger and third finger (See Joint #11 in Figure 3 (a)). The other joint is arranged in the middle of the thumb and is utilized for extension and flexion (See Joint #12 in Figure 3 (a)). By constructing the first finger this way, design concept D) can be realized. Figure 4 (a) shows a picture of HRP-3 gripping a wood panel.

The second finger imitating an index finger has 3 active joints. At the base of second finger, there are rectangular joints, which are made up of joints #21 and #22. Using Joint #21, extension and flexion can be realized. Joint #22 contributes to both abduction and adduction motion. Joint #23 is employed in the middle of second finger for extension and flexion. By making the second finger have 3 D.O.F., simple operation such as pulling the trigger of electrical driver and pushing the electrical switch can be achieved, even if the first finger and the third finger are occupied for grasping. The design concept G) is realized by the second finger.

The third finger, which is imitatively constructed by bundling up middle, ring, and little fingers, has 1 D.O.F. As shown in Figure 3 (a), the third finger has function of extension and flexion by controlling Joint #31. To achieve design concept E) by the third finger, its base, which is a part of the palm, is little bit flexed as shown in Figure 3 (b). Since we can also wrap the third finger with 1 D.O.F. and the first finger with 2 D.O.F. around grasping objects, the design concept F) is achieved. Figures 4 (b) and (c) show snapshots of HRP-3 grasping 350ml can and an electrical drill.

Figure 4 shows how design concepts D) to G) are realized by arranging six joints as shown in Figure 3. Although there is no doubt application tasks performed by HRP-3 and its hand are still limited, it is remarkable that design concept D) to G) can be realized by one hand with so few joints.

(a) Wood panel

(b) 350ml can

(c) Electrical drill

Figure 4. Grasping by HRP-3 hand

## 4. Mechanisms

When working in a real environment, dust-proof and splash-proof functionality are essential. For example, there could be water leaking from the ceiling and a cloud of dust inside the tunnel, when boring using an excavator. To establish key technologies to realize humanoid robots working in the real environment, we developed mechanisms for preventing the penetration of dust or moisture. In Section 4-1, we explain the detail of mechanisms preventing the penetration of dust or moisture together with the cooling system in Sections 4-2 and 4-3.

### 4-1. Dust and splash proof specifications

As our goal to realize a dust and splash proof mechanism, we tried to design HRP-3 in accordance with IEC IP52. For reference, the IP (Ingress Protection) protection classification system is produced in IEC (International Electrotechnical Commission) publication 529, which provides a means of specifying an enclosure on the basis of degree of protection. It does not provide for protection against mechanical damage caused by or within a device. For notation, the letters IP are followed by two numbers. The first digit is an indication as to the degree of protection to solid foreign objects, i.e. dust or fingers. The second digit indicates the degree of protection to ingress of fluids, i.e. splash. To put it concretely, the first digit 5 of IP52 intends protection against the amount of dust that would interfere with normal operation. The second digit 2 of IP52 specifies that the system is protected against vertically falling water drops when enclosure is tilted up to 15 [degrees].

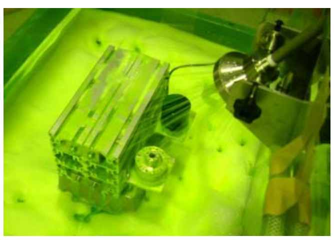
### 4-2. Dust and splash proof mechanism

To achieve our goal, we first evaluated the dust/splash-proof capabilities of individual units, such as the gear box unit and drive unit. We next examined capabilities of developed modules, such as an upper arm module or a chest module. After confirming the dust/splash-proof capabilities both of units and modules, the dust/splash-proof capabilities of the assembled HRP-3 was examined. Figure 5 shows the evaluation tests that we carried out. Figures 5(a) and 5(b) show an overview of dust-proof test and a gear box unit after testing. For dust-proof tests, talcum powder (JIS Z 8901) was used. Figures 5(c) and 5(d) show a gear box unit and upper arm of HRP-3P under going splash-proof tests. For splash-proof tests, we used fluorescent liquid (L-DT).

To analyze route taken by dust and moisture into mechanisms, we evaluated tests as shown in Figure 5. Figure 6 shows splash-proof test results of gear box unit of HRP-2, which is not protected. To clarify, Figure 6 is a snapshot of the “Circular Spline” of a harmonic drive under a special “black light”. The fluorescent green color on a color print (or the white color in monochrome) in Figure 6 tells us that the gear box unit was flooded with fluorescent liquid via its mechanical interface, i.e. “Circular Spline.”

(a) Overview of dust-proof test

(b) Gear unit after dust-proof test



(c) Gear unit under splash-proof test

(d) Upper arm of HRP-3P under splash-proof test

Figure 5. Tests of dust-proof and splash-proof

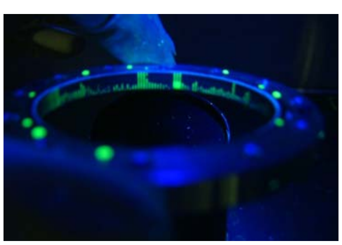


Figure 6. Splash-proof test results
using a gear box of HRP-2

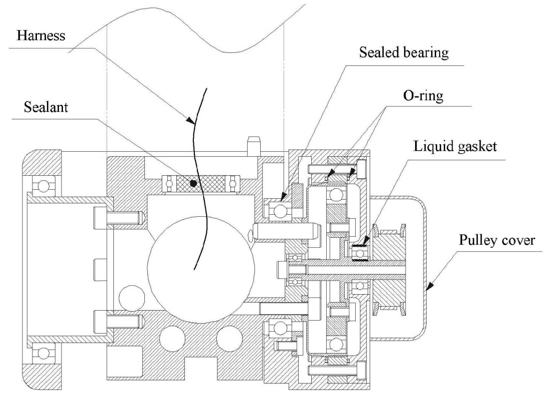



Figure 7. Joint mechanism
with preventing the penetration of dust or splash

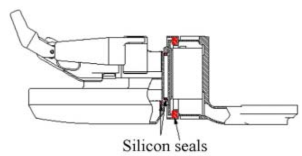



Figure 8. Cover mechanism
with preventing the penetration of dust or splash

Using the methods explained above we designed and evaluated mechanisms that prevent the intrusion of dust and moisture. Figure 7 shows one example of the developed mechanisms, which is a joint mechanism of HRP-3P.

O-rings are seated in grooves and compressed during assembly between the “Circular Spline” and gear box parts. The reason we designed this way comes from evaluation tests as shown in Figure 6. At the interfaces which are difficult to seat o-rings, liquid gaskets are employed. Wherever possible, we selected sealed bearings with to prevent dust and moisture. At interfaces between compartments we used sealant. This was especially effective around harnesses. Although Figure 7 shows the joint mechanism of HRP-3P, dust/splash-proof mechanisms of HRP-3 are basically the same as those of HRP-3P.

Figure 8 shows a section of the mechanism which prevents the penetration of dust and moisture around the wrist of HRP-3. We used several types of silicon seals between various covers.

As shown in Figures 7 and 8, we employed a lot of o-rings, liquid gaskets, sealed bearings, and silicon seals, to realize a mechanism that is both dust and splash-proof. The sealing material employed are products that are used by both industrial and underwater robots [17]. Since humanoid robots have movable joints, we carefully selected parts based on joint friction tests and placed them based on dust/splash-proof evaluation tests.

### 4-3. Cooling mechanism

A cooling mechanism generally requires an intake and exhaust, which usually become areas where dust and moisture penetrate. So therefore, prevention of dust and moisture in these areas are paramount. To overcome this issue, we newly developed the cooling mechanism with preventing the penetration of dust or splash.

In this section, we describe the dust and moisture proof cooling mechanism. The chest module of HRP-3 is the most important part for cooling in HRP-3. The reason is that there are many electrical parts including a CPU board and power modules, such as DC/DC converters, inside. Although Figure 9 shows the cooling mechanism of HRP-3P, the cooling mechanism of HRP-3 is basically the same.

As shown in Figure 9, the developed cooling mechanism consists of an inner shell and an outer shell. Since the inner shell houses electrical parts, it functions as a main barrier preventing the penetration of dust or moisture. Dust/splash-proof filters are used at the intakes of the inner shell. Powerful fans are employed at exhausts of the inner shell to prevent the penetration of dust or moisture. The outer shell is designed to act like an assistant barrier that prevents dust/moisture penetrating the inner shell. Although open areas of the intakes and exhausts of the outer shell are large, they have louvers making it difficult for dust and moisture to penetrate inner shell. To improve dust/splash-proof capability, we designed the cooling system so that the inflow axes of intakes of inner shell aren't in line with those of outer shell. The same is true for the opening for the outflowing air. Even if dust or moisture penetrates the outer shell, it will be pulled out of the outer shell by gravity.

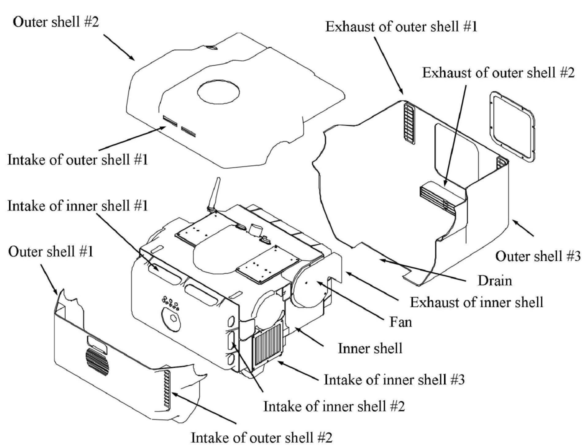



Figure 9.Cooling mechanism

## 5. Electrical system

Here we describe the design methods used for the electrical system, which is also made to be dust and splash proof.

Although HRP-3 was designed in accordance with IEC IP52 as explained in Section 4-1, we tightened up the dust/splash-proof specifications of the arm to IEC IP54. The second digit 4 of IP54 intends protection against water sprayed from all directions. The reason we deigned so is that arm postures during tasks are not fixed. To realize IEC IP54, we need to realize a sealed structure with no openings for intake and exhaust. The motor drivers based on FETs give off a lot of heat. The motor drivers in the arms also use FETs so they generate a lot of heat. So placing them inside of sealed arms was not possible. To overcome this, we placed the motor drivers driving the arms inside of the inner shell together with the CPU board. We also placed the motor drivers driving the head in the chest enclosure because the joints are attached to the head. This is the reason a centralized control system was employed for the arms and head.

With regard to other motor drivers (namely motor drivers driving legs, chest, and hands), the designed cooling mechanisms have an effect on cooling them even if they are placed inside of a link. As a result, a distributed control system is employed for controlling legs, chest, and hands. To achieve the distributed control system, we adopt an internal network based on CAN (Controller Area Network). Although we developed a distributed control system based on real-time Ethernet together with several types of node controller when developing HRP-3P [12, 18], a distributed control system based on CAN is adopted for HRP-3 to improve reliability and maintenance of the system.

From reasons explained above, we adopt both type systems into HRP-3 as shown in Figure 10.

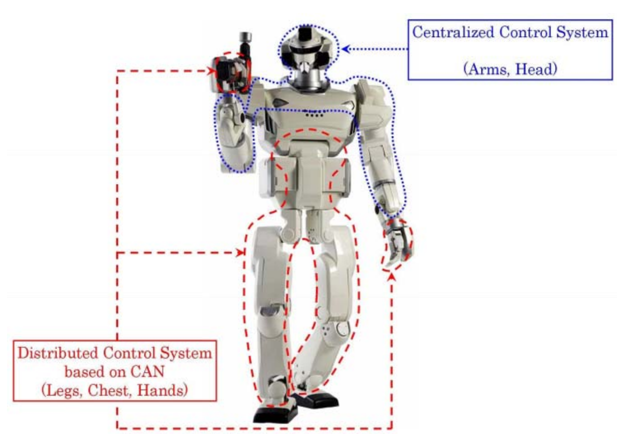



Figure 10. Control systems of HRP-3

## 6. Experiments

At the press-release of the HRP-3 on June 21, 2007, we gave a demonstration of bridge construction work under a simulated outdoor environment with a shower area and a slippery ground area to show the effectiveness of developed HRP-3. In this section, some of demonstration results are presented.

### 6-1. Splash-proof

Figure 11 shows a snapshot of drip-proof demonstration. In this demonstration, we showered HRP-3 with equivalent rainfall of 100 [mm/h]. HRP-3 was successfully able to make stable turning during a shower without any troubles. HRP-3 was also able to continue a demonstration after the shower. This demonstration indicated the effectiveness of the mechanisms preventing the penetration of dust or moisture, which we adopted into HRP-3.

### 6-2. Walk on a low friction floor

In the real environment, we have a lot of unexpected slippery floors. For example, a sudden shower will change the condition between the foot and the ground. Manhole covers with rainwater would also be slippery. A frozen road is another example. It is one of important issues to stabilize biped walking on an unexpected slippery floor with a low friction for practical use. To overcome this, we developed a feedback control system based on a slip observer [19], as a part of software for a humanoid robot in the real environment. This new software is implemented in the HRP-3.

Figure 12 shows a photograph of walking on a low friction floor. In this demonstration, we scattered fine sand, used for sandblasting, on the floor to imitate a low friction floor. The marked area, on which HRP-3 was walking in Figure 12, is the slippery ground area. We measured the friction coefficient using a simulated environment using the sole of the HRP-3 with a dummy weight, which makes heavier to reduce a measured error, and obtained the coefficient value of $\mu = 0.248$ (see Table 2). In laboratory experiments, we tested walking on low friction floor with $\mu = 0.0948$ and stable walking was achieved using the proposed control scheme [20]. This condition of friction floor with $\mu = 0.0948$ is the same as slippery snow [21]. These results confirm the effectiveness both of hardware and software of HRP-3.

### 6-3. Arm/Leg coordination

Figure 13 shows a photograph of the demonstration of bridge construction work. In Figure 13, HRP-3 leans against the bridge using the left-hand to fasten a bolt using an electric drill grasped by the right-hand with the assumption that HRP-3 can't get closer to the bridge. To generate this motion, we used the generalized ZMP, which can be utilized for calculating the stability criterion even if contact points between a humanoid robot and environment doesn't exist in the same plane [22]. Looking at this demonstration, we confirmed the possibility of application tasks performed by HRP-3.

Figure 11. Splash-proof demonstration

Figure 12. Demonstration of walking on a low friction floor

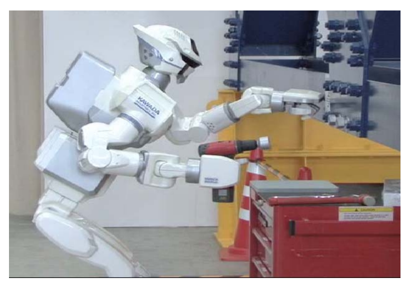


Figure 13. Demonstration of arm/leg coordination

Table 2. Specification on friction coefficient

| | Maximum of Pushing force | Contact force | Friction coefficient |
|---|---|---|---|
| $1^{st}$ trial | 1.33 [kgf] | Robot sole with dummy weight: 4.70 [kgf] | 0.283 |
| $2^{nd}$ trial | 1.06 [kgf] | | 0.226 |
| $3^{rd}$ trial | 1.08 [kgf] | | 0.230 |
| $4^{th}$ trial | 1.16 [kgf] | | 0.247 |
| $5^{th}$ trial | 1.11 [kgf] | | 0.236 |
| $6^{th}$ trial | 1.13 [kgf] | | 0.240 |
| $7^{th}$ trial | 1.31 [kgf] | | 0.279 |
| $8^{th}$ trial | 1.17 [kgf] | | 0.249 |
| $9^{th}$ trial | 1.19 [kgf] | | 0.253 |
| $10^{th}$ trial | 1.11 [kgf] | | 0.236 |
| Average | 1.17 [kgf] | 4.70 [kgf] | 0.248 |

## 7. Conclusions

This paper presented how we developed the humanoid robot: HRP-3. The main mechanical and structural components of HRP-3 were designed to prevent the penetration of dust or moisture in accordance with IEC IP52. We successfully made a demonstration of HRP-3 under 100 [mm/h] shower.

Future work includes evaluating developed HRP-3 through experiments. An experiment on operating HRP-3 in the open air and in the rain is one which we would like to test. An improvement of HRP-3, which reflects user's feedback during experimental tests, is also our future work. Our desire is to put the HRP-3 to practical use and creating a real market for humanoid robots.

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## References

[1] J. S. Mehling, P. Strawser, L. Bridgwater, W. K. Verdeyen, and R. Rovekamp, "Centaur: NASA's Mobile Humanoid Designed for Field Work," Proc. IEEE Int. Conference on Robotics and Automation, pp. 2928-2933, 2007.

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

[3] 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.

[4] 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.

[5] S. Lohmeier, T. Buchmann, M. Schwienbacher, H. Ulbrich, and F. Pfeiffer, "Leg Design for a Humanoid Walking Robot," Proc. IEEE-RAS Int. Conference on Humanoid Robots, pp. 536-541, 2006.

[6] I. W. Park, J. Y. Kim, J. Lee, and J. H. Oh, "Mechanical Design of Humanoid Robt Platform KHR-3 (KAIST Humanoid Robot – 3: HUBO)," Proc. IEEE-RAS Int. Conference on Humanoid Robots, pp. 321-326, 2005.

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

[8] 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.

[9] 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.

[10] H. Inoue, S. Tachi, Y. Nakamura, K. Hirai, N. Ohyu, S. Hirai, K. Tanie, K. Yokoi, and H. Hirukawa, "Overview of Humanoid Robotics Project of METI," Proc. the 32nd Int. Symposium on Robotics, pp. 1478-1482, 2001.

[11] K. Akachi, K. Kaneko, N. Kanehira, S. Ota, G. Miyamori, M. Hirata, S. Kajita, and F. Kanehiro, "Development of Humanoid Robot HRP-3P," Proc. IEEE-RAS Int. Conference on Humanoid Robots, pp. 50-55, 2005.

[12] F. Kanehiro, K. Kaneko, K. Fujiwara, K. Harada, S. Kajita, K. Yokoi, H. Hirukawa, K. Akachi, and T. Isozumi, "The first Humanoid Robot that has the Same Size as a Human and that can Lie down and Get up," Proc. IEEE Int. Conference on Robotics and Automation, pp. 1633-1639, 2003.

[13] J. Butterfaß, M. Grebenstein, H. Liu, and G. Hirzinger, "DLR-Hand II: Next Generation of a Dextrous Robot Hand," Proc. IEEE Int. Conference on Robotics and Automation, pp. 109-114, 2001.

[14] K. Hirai and S. Nakayama, "Production of a Robot Platform and Development of Intelligent Robot Hands," Journal of the Robotics Society of Japan, Vol. 19, No. 1, pp. 8-15, 2001 (in Japanese).

[15] K. Hoshino and I. Kawabuchi, "Stable pinching with fingertips in humanoid robot hand," Proc. IEEE/RSJ Int. Conference on Intelligent Robots and Systems, pp. 3815-3820, 2005.

[16] K. Kaneko, K. Harada, and F. Kanehiro, "Development of Multi-fingered Hand for Life-size Humanoid Robots," Proc. IEEE Int. Conference on Robotics and Automation, pp. 913-920, 2007.

[17] H. Yamada, S. Shigisaki, M. Mori, K. Takita, K. Ogami, and S. Hirose, "Development of Amphibious Snake-like Robot ACM-R5," Proc. 36th International Symposium on Robotics, TH3C4.pdf, 2005.

[18] F. Kanehiro, Y. Ishiwata, H. Saito, K. Akachi, G. Miyamori, T. Isozumi, K. Kaneko, and H. Hirukawa, "Distributed Control System of Humanoid Robots based on Real-time Ethernet" Proc. IEEE/RSJ Int. Conference on Intelligent Robots and Systems, pp. 2471-2477, 2006.

[19] 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.

[20] New Energy and Industrial Technology Development Organization (in Japan), "Research Report of a development of fundamental technologies for a humanoid robot in a real environment," March 2006 (in Japanese).

[21] "Manual of Northern Road," Report by Independent Administrative Institution Civil Engineering Research Institute of Hokkaido, http://www2.ceri.go.jp/koutsuu/rkanri_m.htm, (in Japanese).

[22] K. Harada, S. Kajita, K. Kaneko, and H. Hirukawa, "ZMP Analysis for Arm/Leg Coordination" Proc. IEEE/RSJ Int. Conference on Intelligent Robots and Systems, pp. 75-81, 2003.