2007 IEEE International Conference on
Robotics and Automation
Roma, Italy, 10-14 April 2007

Development of Multi-fingered Hand for Life-size Humanoid Robots

Kenji KANEKO, Kensuke HARADA, and Fumio KANEHIRO

Abstract — This paper presents a development of multi-fingered hand, which is modularized and can be attached to life-size humanoid robots. The developed hand has four fingers with 17 joints, which consist of 13 active joints and 4 linked joints. A miniaturized 6-axes force sensor is newly developed and is mounted on each fingertip for improving the manipulability. A main node controller with I/O, motor drivers, and amplifiers for 6-axes force sensors are also newly developed. These components are equipped in the hand for modularization. The developed hand is designed so as to realize about 8 [N] forces on the pad point of stretched finger, supposing transmission efficiency of drive system is 55 [%]. In this paper, the mechanisms of hand module, its specifications, and electrical system are also introduced.

1. Introduction

The needs for robots have recently been changed from factory automation to human friendly robot system. Coming increasingly aging societies, the realization of robots that assist human activities in human daily environments such as in offices, homes and hospitals is required. In the future, a humanoid robot, which can walk bipedally and perform skilful tasks by dual-arm with hands, would be one of ultimate robots that have an ability of cooperative and coexistence with humans, because of anthropomorphism, friendly design, applicability of locomotion, behavior within the human living environments, and so on.

The research on humanoid robots is currently one of the most exciting topics. It is no exaggeration to say that the great success of HONDA humanoid robot makes the current research on the world's humanoid robot to become very active area [1-3]. Since the second prototype HONDA humanoid robot: P2 was revealed in 1996, many biped humanoid robots have been developed [4-15]. The newest ASIMO, which debuted with a capability of running at 6 [km/h] on December 13, 2005, will increasingly make the research on locomotion of humanoid robots active.

However, application tasks performed by current humanoid robots are discouragingly limited. A 1 D.O.F. hand of HRP-2 [10] was exclusively designed for grasping a panel. The first ASIMO [3] and the newest ASIMO have a 1 D.O.F. hand and a 2 D.O.F. hand respectively, though they have 5 fingers. ASIMO has a weak grip and is able to exert a squeeze of only 0.3 [kg]. ASIMO can't handle heavy objects, but grasp light objects such as mobile phone. In addition, ASIMO now crushes a raw egg in the hand because of mechanism driving 5 fingers by one actuator and wire. HUBO has also 5 fingers [14]. Each finger is driven using pulley-bet drive system with an actuator and a planetary gear head [13]. The hand of HUBO has a little dexterity because of a 5 D.O.F. hand, but is not sufficient for manipulation. Consequently, the development and application of a multi-fingered hand, which can be attached to life-size humanoid robots and has a high performance of a human hand, would greatly be expected to expand the possible application tasks of humanoid robots.

On the other hand, a lot of research activities on the multi-fingered robot hand have been carried out in the past few years [16-19]. Various approaches to achieve dexterous manipulation by a robot hand have been trialed. Not only the theoretical approach for constructing control algorithms, but also several multi-fingered hand systems have been developed for experimental investigation [20-31]. DLR Hands: DLR Hand I [23], DLR Hand II [24], and HIT/DLR Dexterous Hand [25] are well known as one of leading robot hands. DLR Hand II consists of four identical fingers with 17 joints and 13 D.O.F. and can realize 30 [N] forces at the fingertip. All components including actuation system, sensors, and the communication electronics is completely integrated in the hand for easy interfacing to different robots. However, DLR Hand II is too large for life-size humanoid robots. HIT/DLR Hand, which is a little miniaturized by re-designing based on DLR Hand II and can realize 10 [N] forces at the fingertip, is still large for life-size humanoid robots. Gifu Hand II [27], which has 5 fingers with 20 joints and 16 D.O.F., is also large for life-size humanoid robots. Since DLR Hands and Gifu Hand employ the differential bevel gear transmission system, there is a fear that a backlash of transmission system disturbs dexterous manipulations. From sized and modularized viewpoints, Universal_Hand [30] may be the best robot hand for life-size humanoids. It has 5 fingers and a palm, which are just human size. CAN communication system is integrated inside of the palm. However, it is not sufficient for dexterous manipulation because of a wire drive system. Although Shadow Robot Hand [31] is human size and has 5 fingers, it requests 40 air muscles mounted on the forearm.

Manuscript submitted to 2007 IEEE International Conference on Robotics and Automation.

The authors are with Humanoid Research Group, Intelligent Systems Research Institute, National Institute of Advanced Industrial Science and Technology (AIST), 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan (e-mail: {k.kaneko, kensuke_harada, f-kanehiro} @aist.go.jp).

This paper presents a development of multi-fingered hand, which is modularized and can be attached to life-size humanoid robots. The final aim of our development is to expand the possible application tasks of life-size humanoid robots by equipping them with multi-fingered hands. To achieve our goal, the developed hand is carefully designed according to our design policies. In the Section 2, the design policies are explained. In the Sections 3, 4 and 5, the mechanisms of hand module, its specifications, and electrical system are also introduced.

2. Design Policies

In order to realize a life-size multi-fingered hand, the developed hand is carefully designed according to our design policies. In this section, we explain the design policies, which are decided by considering predecessor's works, current robotics technologies, and our aim.

2-1. Design Policy #1: Human Size

From an anthropomorphism viewpoint, the size of hand should match life-size humanoid robots. Referring Japanese standard man [32], it is settled as a target to realize about 180 [mm] hand length from crease and about 84 [mm] hand breadth as shown in Figure 1.

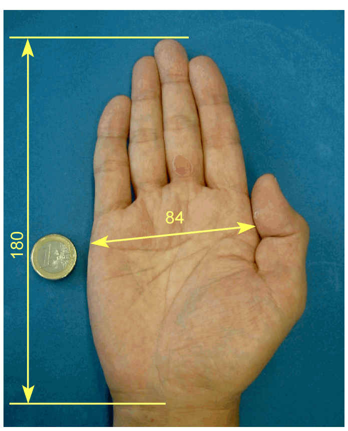


Figure 1. Standard hand size of Japanese man

2-2. Design Policy #2: Humanlike Fingertip Force

To make a multi-fingered robot hand perform skilful tasks as well as a human, it is desirable that the hand generates about the same fingertip force that a human has. It is known that an operational force is about 15 [N] when human upper limbs with finger push objects [33]. Since operational forces depend on finger positions, we have set a goal to realize about 5 [N] maximum forces on the pad point of stretched finger and about 15 [N] maximum forces at the fingertip of bended finger, supposing transmission efficiency of drive system is 55 [%].

2-3. Design Policy #3: Lesser Backlashes

Both to control finger positions accurately and to realize fingertip force precisely, a high stiffness mechanism is required. To achieve this requirement, neither the wire drive system nor the differential bevel gear transmission system is adopted. We adopt a harmonic drive gear transmission system for all active joints to realize lesser backlashes.

2-4. Design Policy #4: Modularization

For easy interfacing to different life-size humanoid robots, it is desirable that all components including actuation system, sensors, and the communication electronics is completely integrated in the hand. However, an electrical power is supplied from the outside of the hand, since the majority of life-size humanoid robots have its own batteries. Fingers composing the hand are also basically modularized as a finger module, which is utilized as fingers except for the thumb, both to reduce the number of component parts and to increase the ability of maintenance.

2-5. Design Policy #5: Joint Structure

To imitate humanlike motion as similar as possible, the joint structure is considered by referencing phalanges of human hand. We design the finger module to have 4 joints and 3 D.O.F. According to the medical technical terms, we call these joints MP joint (**M**etacarpo**p**halangeal joint), PIP joint (**P**roximal **i**nter**p**halangeal joint), and DIP joint (**D**istal **i**nter**p**halangeal joint), while MP joint has mechanically 2 sub-joints. In addition, we design MP joint to consist of two rectangular axes, which are independently driven by its own actuator. PIP joint and DIP joint have one degree of motion respectively. Since human PIP joint and DIP joint work together in many cases, we design PIP joint and DIP joint to be mechanically coupled and driven by one actuator. To achieve stable grasping, precise manipulation, and modularization, a thumb is designed from introducing an additional joint with 1 D.O.F. into the finger module and a little modifying the finger module. As a result, the thumb has 5 joints and 4 D.O.F. These joints are called CM joint (**C**arpo**m**etacarpal joint), MP joint, and IP joint (**I**nter**p**halangeal joint) according to the medical technical terms, while CM joint has mechanically 3 sub-joints. MP joint and IP joint have one degree of motion respectively. They are mechanically coupled and driven by one actuator.

2-6. Design Policy #6: Number of Fingers

To manipulate a grasped object with 3-axes translational motion and 3-axes rotational motion redundantly, at least 3 finger modules with 3 D.O.F. are required [34]. Although the hand with 5 fingers is human-like, it may become bigger. Finally, we aim to realize the hand with from 3 to 5 fingers including the thumb, satisfying design policies #1 to #5.

2-7. Design Policy #7: Fingertip Force Sensor

To achieve stable grasping and precise manipulation, force information imposed on each fingertip is essential. We attempt to develop a miniaturized 6-axes force sensor mounted on the fingertip.

2-8. Design Policy #8: Communication System

To perform application tasks smoothly as well as human, it is necessary to control a hand in collaboration with a humanoid robot with which the hand is equipped. A communication system should be integrated in the hand.

3. Specifications of Developed Multi-fingered Hand

Following our design policies described above, we developed the life-size multi-fingered hand.

Figures 2 and 3 show the developed hand and its kinematical design, respectively. The coordinate system, joint names, and finger names utilized in this paper are also illustrated in Figure 3. Table 1 introduces its principal specifications.

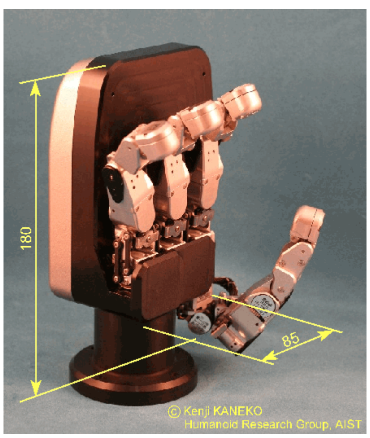


Figure 2. Developed life-size multi-fingered hand

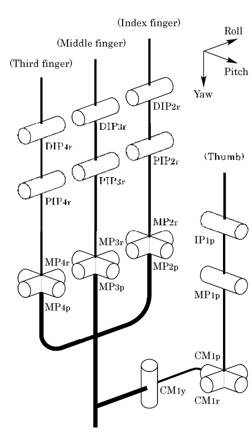


Figure 3. Kinematics of developed multi-fingered hand

Looking at Figure 2, it is apparent that the developed hand has 4 fingers. We also observe that the length and breadth of realized hand are much the same as ones of Japanese standard man. Although the developed hand has only 4 fingers, we could make it have dexterity.

Figure 3 tells us that an identical finger called the finger module is adopted for the index, middle, and third fingers. The finger module has 4 joints, which consists of 3 active joints and 1 linked joint. DIP joint works together with PIP joint. The pitch axis of MP joint of finger module enables adduction and abduction. Other axes enable flexion and extension. The detail mechanics of finger module will be explained in the later section. Figure 3 also informs us that the thumb is designed by introducing an additional joint with 1 D.O.F. between a little modified finger module and a palm. This extra joint of thumb, that is the yaw axis of CM joint, enables flexion and rotation. The roll axis of CM joint of thumb enables adduction and abduction. Other axes enable flexion and extension.

As listed in Table 1, the developed hand has in total 17 joints, which consist of 13 active joints and 4 linked joints. Each active joint is independently driven by own electrical servomotor though a transmission system, which has a super-miniaturized harmonic drive gear. Table 2 shows the specifications of active joint. These are obtained while considering efficiencies of transmission system.

Table. 1 Principal specifications of multi-fingered hand

Dimensions	Length *1	180 [mm]
	Breadth *2	85 [mm]
Fingers		4 [fingers]
Joints		Total 17 [joints]
	Thumb *3	5 [joints]
	Others *4	3 Fingers × 4 [joints]
D.O.F.		Total 13 D.O.F.
	Thumb *5	4 D.O.F.
	Others *6	3 Fingers × 3 D.O.F.
Sensors	Joints	Incremental encoders
	Fingertips	6-axes force sensor
Drive system		Servomotor + Harmonic drive gear
Power system		External DC 48 [V] External DC 12 [V]
Communication system		Ethernet
Weight		1,140 [g]

*1: Length between wrist and fingertip
*2: Width of base attaching index , middle and third fingers
*3: 1-axis IP joint, 1-axis MP joint, 3-axes CM joints
*4: 1-axis DIP joint, 1-axis PIP joint, 2-axes MP joints
*5: IP joint is linked joint working together with MP joint.
*6: DIP joint is linked joint working together with PIP joint.

Table. 2 Active joint specifications of finger module

Joint	MP		PIP
Axis	Roll	Pitch	Roll
Max. momentary torque [Nm]	1.1	0.4	0.4
Max. output speed [rpm]	Approx. 40		

4. Mechanisms

In this section, a principle of mechanisms of developed hand is presented. The finger module, which is utilized for the index, middle and third fingers, is mainly explained. Although the thumb of developed hand is a little modified from the finger module, its principle of mechanism is quite the same as that of finger module.

Figure 4 shows a top view [view in the direction of pitch axis] and side view [view in the direction of roll axis] of developed finger module. In Figure 4, the rotational axis of joint is also illustrated by using a dot-dash line. The names of link and mechanisms utilized in this paper are also illustrated in this figure. In the finger module, there are three servomotors and three super-miniaturized harmonic drive gears.

By using Figure 4, the detail mechanisms are explained as follows.

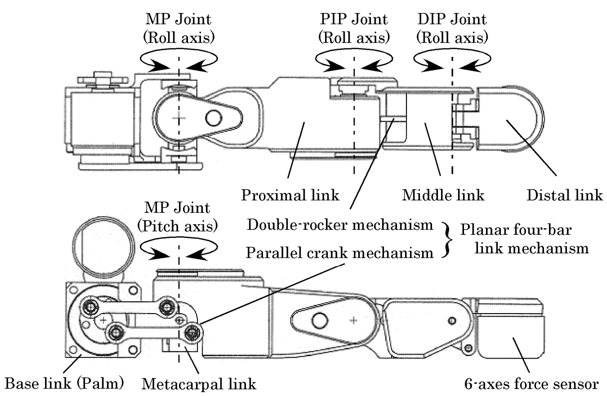


Figure 4. Finger module mechanism

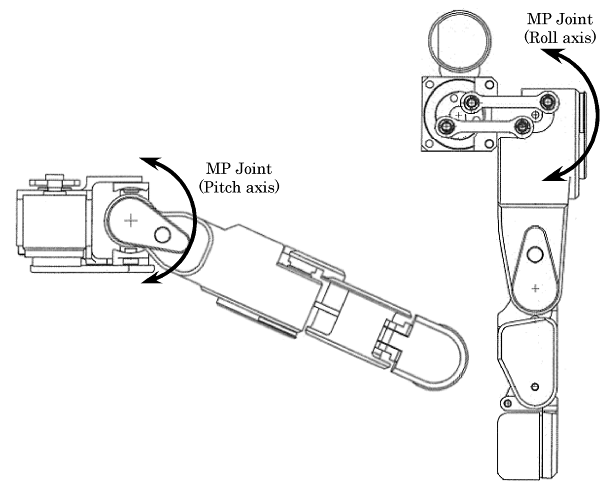
4-1. MP Joint of Finger Module

Explaining from a medical viewpoint, MP joint is defined as a joint between a metacarpal and a proximal phalanx. To realize this medical MP joint, we design a mechanical MP joint to have 2 sub-joints. One is MP roll joint that is a joint between a metacarpal link and a base link attached to a palm. The other is MP pitch joint that is a joint between a proximal link and the metacarpal link. In addition, we design these sub-joints to be orthogonal.

To drive MP roll joint, the first servomotor and the first super-miniaturized harmonic drive gear are integrated to the base link. A parallel crank mechanism is adopted between an output shaft of harmonic drive gear and the metacarpal link.

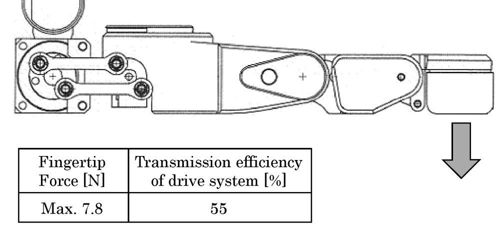
To drive MP pitch joint, the second servomotor and the second super-miniaturized harmonic drive gear are integrated inside of the proximal link. The second harmonic gear is incorporated in MP pitch joint. Its output shaft is directly connected to the metacarpal link. By controlling the second servomotor, MP pitch joint can be controlled.

Constructing MP joint explained above, MP roll joint and MP pitch joint can be controlled independently. Figure 5 shows an example of posture by driving MP joint.



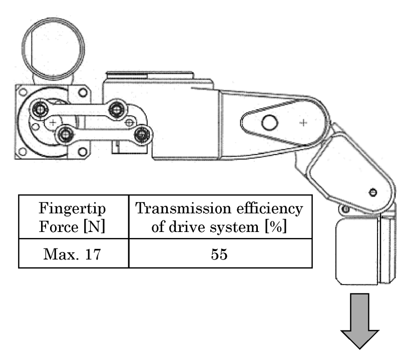
(a) Roll joint (b) Pitch joint

Figure 5. Example of posture by driving MP joint



Fingertip Force [N]	Transmission efficiency of drive system [%]
Max. 7.8	55

(a) Stretched position



Fingertip Force [N]	Transmission efficiency of drive system [%]
Max. 17	55

(b) Bended position

Finger 6. Example of posture by driving PIP joint and Fingertip force

4-2. PIP Joint and DIP Joint of Finger Module

As shown in Figure 4, PIP joint and DIP joint are designed by referencing phalanges of human hand. PIP joint is a joint between the proximal link and a middle link. DIP joint is a joint between the middle link and a distal link. Since human PIP joint and DIP joint work together in many cases, we design PIP joint and DIP joint to be mechanically coupled and driven by one actuator. To couple these joints, a double-rocker mechanism is adopted [25-27].

In the developed hand, we design that PIP joint is an active joint and DIP joint is a linked joint. The reason is related with a position of the third servomotor driving these joints. Since the fingertip force sensor is mounted on the distal link and a connecting rod of the double-rocker mechanism occupies the inner space of the middle link, the third servomotor can't be integrated to these links. Referencing phalanges of human hand, the length of proximal phalanx is much longer compared with that of middle phalanx and that of distal phalanx. The third servomotor is therefore integrated to the proximal link. The third harmonic gear is incorporated in PIP joint. Its output shaft is directly connected to the middle link. By controlling the third servomotor, PIP joint can be controlled actively and DIP joint can be driven via the double-rocker mechanism. Figure 6 shows an example of posture by driving PIP joint.

4-3. Double-Rocker Mechanism

We adopt a unique double-rocker mechanism for the developed finger module.

As regards the majority of robot hands with the double-rocker mechanism, its mechanism is designed so that DIP joint angle engages with DIP joint angle almost linearly. Figure 7 shows an example of general double-rocker mechanism. This design has the advantage of calculating the fingertip position easily. It may be no practical issue to calculate it by using approximated joint angle instead of correct joint angle. However, this design has the disadvantage of energy. The power of motor driving PIP joint and DIP joint is always utilized for them. It can't be expected to generate the powerful fingertip force at the stretched finger position.

Conversely, we design the double-rocker mechanism to have a singular position of the mechanism around the stretched finger position as shown in Figure 8. As a result, relation between PIP joint angle and PIP joint angle is completely non-linear around the stretched finger position. Figure 9 shows its relation of developed finger module. In Figure 9, we plot PIP and DIP joint angles in horizontal axis and vertical axis respectively so that the initial position is the stretched finger position. Figure 10 shows that the ratio of increase from PIP joint speed to DIP joint speed. As shown in Figure 10, its increase ratio can be reduced around the stretched finger position by adopting our unique mechanism. Put another way, our unique mechanism provides the transmission system from servomotor speed to DIP joint speed with higher final reduction ratio around the stretched finger position. This means that the fingertip force is improved by our unique mechanism.

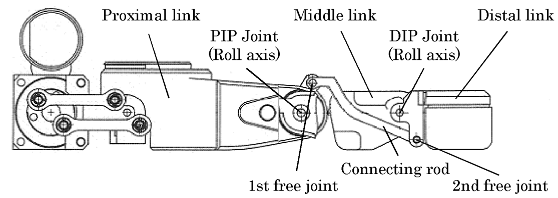


Figure 7. Example of general double-rocker mechanism

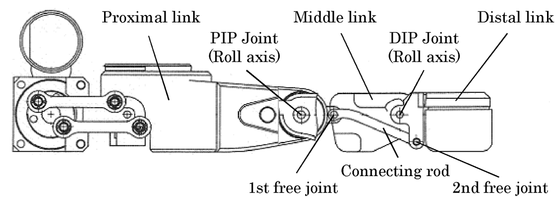


Figure 8. Double-rocker mechanism of developed hand

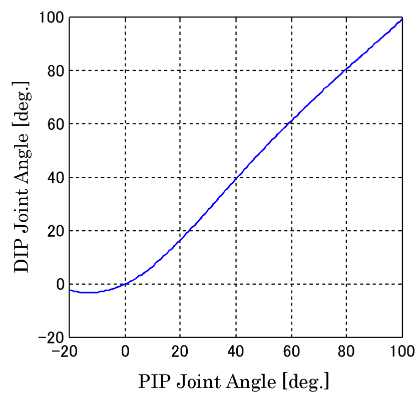


Figure 9. Relation between PIP and DIP joint angles

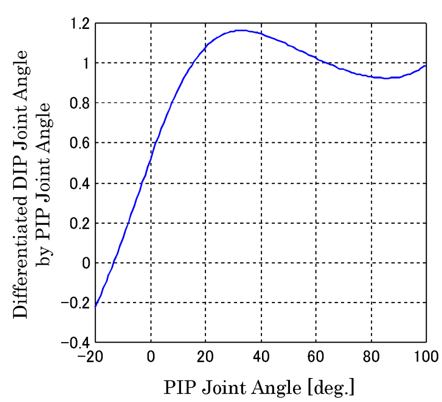


Figure 10. Increase ratio from PIP to DIP joint speeds

Figure 11. Developed hand grasping a screwdriver

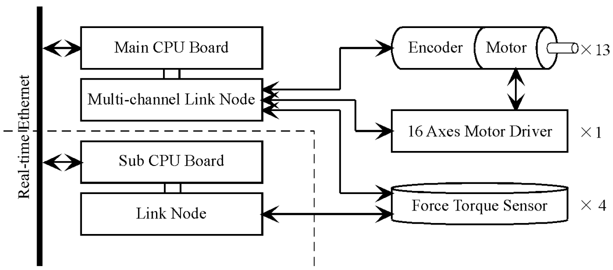


Figure 12. Electrical system of multi-fingered hand

Adopting this unique mechanism, we can utilize the power of motor for driving PIP joint mainly when the finger position is almost stretched. While the power of motor is utilized for driving PIP joint and DIP joint as usual at the bended finger position. As a result, we can realize about 7.8 [N] maximum forces on the pad point of stretched finger and about 17 [N] maximum forces at the fingertip of bended finger, supposing transmission efficiency of drive system is 55 [%], as shown in Figure 6.

The disadvantage of our mechanism is that we need complicated computation to get DIP joint angle. However, this issue is not serious because of a current powerful computer.

Now let us consider the effect of our unique mechanism. If the double-rocker mechanism is designed as usual, we may realize about 6.8 [N] maximum forces on the pad point of stretched finger, supposing the same transmission efficiency of drive system. It means that the fingertip force increases 15 [%] by our unique mechanism. Since the robot hands have not enough inner space, it is difficult to employ more powerful servomotors to realize more powerful fingertip force. A 15 [%] increase is progressive and is especially effective at grasping as shown in Figure 11.

5. Electrical System

Figure 12 shows an entire electrical system of the developed multi-fingered hand. In this section, the electrical system is presented by introducing newly developed electrical components.

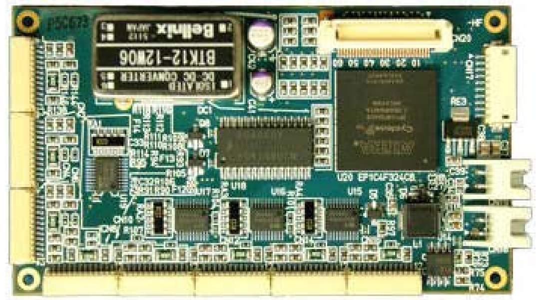


Figure 13. Node I/O board: HRP-3P-MCN

Table. 3 Specifications of HRP-3P-MCN

AD	Channel	16 [ch]
	Resolution	12 [bit]
PWM	Channel	16 [ch]
	Resolution	11 [bit]
Counter	Channel	16 [ch]
	Resolution	24 [bit]
DIO	Channel	32 [ch]
	Feature	Switched between IN or OUT
Size		55 [mm]×95 [mm]×1.6 [mm]
Supply Voltage		DC 12.0 [V] ± 10%
Consumption Current		1.2 [A] (typical)

5-1. CPU Board

For easy interfacing to different life-size humanoid robots, a main node controller, which consists of a CPU board and an I/O board, is equipped in the developed hand.

The CPU board, which is running a hard real-time Linux, is the same as that developed for humanoid robot HRP-3P [35]. A CPU is SH4 with 240 [MHz] and the operating system is ART-Linux, which is a real time extension of Linux [36]. This CPU board is card size (55 [mm] × 95 [mm]) and is utilized with the I/O board for constructing node controller. One of I/O boards can be stacked up on this CPU board. The depth at stacking an I/O board is 22.7 [mm]. This CPU board also has two Ethernet ports and we use these Ethernet ports for real-time communication by employing the real-time Ethernet system we developed [36].

5-2. Multi-channel Link Node

Several I/O boards were developed for HRP-3P [35]. However, these boards can a few channels of I/O. Since the developed hand has 13 D.O.F., a board with multi-channel I/O, which can control the developed hand, is required to save inner space of the hand.

Figure 13 shows a new I/O board, which is newly developed for our multi-fingered hand and is named multi-channel link node: HRP-3P-MCN. The developed I/O board has 16 channels of 12 [bit] AD for importing data from analog sensors. 16 channels of 11 [bit] PWM output, 16 channels of 24 [bit] Counter, and 32 channels of DIO, are also prepared for controlling motors. The size of this I/O board is the same as that of the CPU board to stack up. Table 3 lists its practical specifications.

5-3. Other Electrical Components

A motor driver board, which consists of several MOS-FET bridge drivers, is also newly developed for our hand. This driver board is capable of controlling 16 motors with the same channels of PWM output of multi-channel link node: HRP-3P-MCN. A carrier frequency of PWM is approximately 20 [kHz] not to give noise to humans. To put it easily on the top of other boards, such as the CPU board and I/O boards, we design the driver board to have the same size (55 [mm] × 95 [mm]) as other boards.

A miniaturized 6-axes force sensor is developed too, and is mounted on each fingertip for improving the manipulability, as shown in Figure 4. The structure of the developed force sensor is the same as that of majority of robotic force sensor based on strain gauges. Since its output is analog signal, an amplifier board for force sensors is also newly developed. In common with other boards, the amplifier board is constructed on one board whose size is 55 [mm] × 95 [mm] because of easy assembling. Figure 14 shows the developed amplifier board for force sensors.

Figure 14. Amplifier board for force-torque sensors

6. Conclusions

This paper presented how we developed the multi-fingered hand, which is modularized and can be attached to life-size humanoid robots. The developed hand has four fingers with 17 joints, which consist of 13 active joints and 4 linked joints. A main node controller with I/O, motor drivers, miniaturized 6-axes force sensors, and amplifiers for force sensors, which are also newly developed, are equipped in the hand for modularization. For realization of powerful fingertip force, we adopt a unique mechanism. The mechanisms of hand module, its specifications, and electrical system are also introduced in this paper.

Future works include evaluating the developed multi-fingered hand through a lot of experiments. Based on the experimental evaluations, we are going to figure out the parts that we will modify to improve the performance. The palm design aiding power grasping will be investigated, while the developed hand has the flat palm. Constructing stable gasp control and dexterous manipulation control is also one of our future works. An experiment on whole-body manipulation by humanoid robots HRP-2 [10] and HRP-3P [35] with developed hands will also be investigated in the future. Figure 15 shows the humanoid robot HRP-3P with developed hand. The realization of skillful application tasks by life-size humanoid robots with multi-fingered hands is one of them that we should achieve in the future.

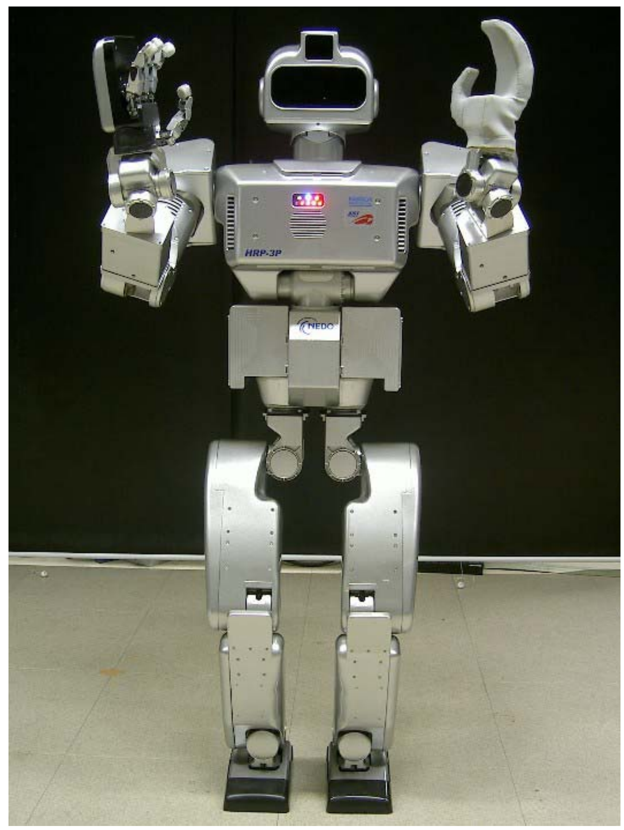


Figure 15. Humanoid robot HRP-3P with developed hand
The right hand : developed hand presented in this paper
The left hand : original hand developed for HRP-3P

Acknowledgments

The authors would like to express sincere thanks to the staff of Humanoid Research Group, AIST, for their significant comments. The authors are also grateful to people engaged in producing components of the developed hand for their kindness supports.

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] K. Nishiwaki, T. Sugihara, S. Kagami, F. Kanehiro, M. Inaba, and H. Inoue, "Design and Development of Research Platform for Perception-Action Integration in Humanoid Robot: H6," Proc. IEEE/RSJ Int. Conference on Intelligent Robots and Systems, pp. 1559-1564, 2000.

[5] G. Wang, Q. Huang, J. Geng, H. Deng, and K. Li, "Cooperation of Dynamic Patterns and Sensory Reflex for Humanoid Walking," Proc. IEEE Int. Conference on Robotics and Automation, pp. 2472-2477, 2003.

[6] Q. Huang, Z. Peng, W. Zhand, L. Zhang, and K. Li, "Design of Humanoid Complicated Dynamic Motion based on Human Motion Capture," Proc. IEEE/RSJ Int. Conference on Intelligent Robots and Systems, pp. 686-691, 2005.

[7] Y. Kuroki, T. Ishida, J. Yamaguchi, M. Fujita, and T. Doi, "A Small Biped Entertainment Robot," Proc. IEEE-RAS Int. Conference on Humanoid Robots, pp. 181-186, 2001

[8] Y. Kuroki, M. Fujita, T. Ishida, K. Nagasaka, and J. Yamaguchi, "A Small Biped Entertainment Robot Exploring Attractive Applications," Proc. IEEE Int. Conference on Robotics and Automation, pp. 471-476, 2003.

[9] K. Nagasaka, Y. Kuroki, S. Suzuki, Y. ITOH, and J. Yamaguchi, "Integrated Motion Control for Walking, Jumping and Running on a Small Bipedal Entertainment Robot," Proc. IEEE Int. Conference on Robotics and Automation, pp. 3189-3194, 2004.

[10] 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.

[11] M. Gienger, K. Löffler, and F. Pfeiffer, "Towards the Design of Biped Jogging Robot," Proc. IEEE Int. Conference on Robotics and Automation, pp. 4140-4145, 2001.

[12] K. Löffler, M. Gienger, and F. Pfeiffer, "Sensor and Control Design of a Dynamically Stable Bipe Robot," Proc. IEEE Int. Conference on Robotics and Automation, pp. 484-490, 2003.

[13] I. W. Park, J. Y. Kim, S. W. Park, and J. H. Oh, "Development of Humanoid Robot Platform (KAIST Humanoid Robot – 2)," Proc. IEEE-RAS Int. Conference on Humanoid Robots, CD-ROM 29_paper.pdf, 2004.

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

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

[16] H. Hanafusa and H. Asada, "Stable Prehension by a Robot Hand with Elastic FIngers," Proc. 7th Int. Symp. On Industrial Robots, pp. 361-368, 1997.

[17] J. K. Salisbury, "Kinematic and Force Analysis of Articulated Mechanical Hands," Ph. D. Thesis, Dept. of Mechanical Engineering, Stanford University, 1982.

[18] B. S. Baker, S. Fortune, and E. Grosse, "Stable Prehension with a Multi-fingered Hand," Proc. IEEE Int. Conference on Robotics and Automation, pp. 570-575, 1985.

[19] J. Kerr and B. Roth, "Analysis of Multifingered Hands," Int. J. Robotics Research, Vol. 4-4, pp. 3-17, 1986.

[20] J. K. Salisbury and J. J. Craig, "Articulated Hands: Force Control and Kinematic Issues," Int. J. Robotics Research, Vol. 1-1, pp. 4-17, 1982.

[21] S. C. Jacobsen, E. K. Iversen, D. F. Knutti, R. T. Johnson, and K. B. Biggers, "Design of the Utah/M.I.T. Dexterous Hand," Proc. IEEE Int. Conference on Robotics and Automation, pp. 1520-1532, 1986.

[22] H. Maekawa, K. Yokoi, K. Tanie, M. Kaneko, N. Kimura, and N. Imamura, "Development of a Three-fingered Robot Hand with Stiffness Control Capability," Mechatranocs, Vol. 5, No. 5, pp. 483-494, 1992.

[23] G. Hirzinger, J. Butterfaß, M. Fischer, M. Grebenstein, M. Hähnel, H. Liu, I. Schaefer, and N. Sporer, "A Mechatronics Approach to the design of light-weight arms and multifingered hands," Proc. IEEE Int. Conference on Robotics and Automation, pp. 46-54, 2000.

[24] 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.

[25] P. He, M. H. Jin, L. Yang, R. Wei, Y. W. Liu, H. G. Cai, H. Liu, N. Seitz, J. Butterfaß, and G. Hirzinger, "High Performance DSP/FPGA Controller for Implementation of HHIT/DLR Dexterous Robot Hand," Proc. IEEE Int. Conference on Robotics and Automation, pp. 3397-3402, 2004.

[26] 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).

[27] H. Kawasaki, T. Komatsu, and K. Uchiyama, "Dexterous Anthropomorphic Robot Hand with Distributed Tactile Sensor: Gifu Hand II," IEEE/ASME Transactions on Mechatronics, Vol. 7, No. 3, pp. 296-303, 2002.

[28] A. Namiki, Y. Imai, M. Ishikawa, M. Kaneko, "Development of a High-speed Multifingerd Hand System and Its Application to Catching," Proc. IEEE/RSJ Int. Conference on Intelligent Robots and Systems, pp. 2666-2671, 2003.

[29] S. Roccella, M. C. Carrozza, G. Cappiello, P. Dario, J. J. Cabibihan, M. Zecca, H. Miwa, K. Itoh, M. Matsumoto, and A. Takanishi, "Design, fabrication and preliminary results of a novel anthropomorphic hand for humanoid robotics: RCH-1," Proc. IEEE/RSJ Int. Conference on Intelligent Robots and Systems, pp. 266-271, 2004.

[30] 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.

[31] Shadow Robot Company, "Shadow Dexterous Hand C5 – Technical Specification," http://www.shadowrobot.com/downloads/shadow_dextrous_hand_technical_specification_C5.pdf

[32] Research Institute of Human Engineering for Quality Life (in Japan), "Research Report concerning Digital Hand Technology," Research Report of HQL, 15-R-2, March 2004 (in Japanese).

[33] National Institute of Technology and Evaluation (in Japan), "Human Characteristics Database," Database of NITE.

[34] M. Kaneko, "Parallel Mechanisms in Multi-fingered Robot Hands," Journal of the Robotics Society of Japan, Vol. 10, No. 6, pp. 739-744, 1992 (in Japanese).

[35] 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.

[36] 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.