

# Pinching at finger tips for humanoid robot hand

Kiyoshi Hoshino (University of Tsukuba) and Ichiro Kawabuchi (TechExperts, Inc.)

**Abstract**— It is difficult to generate the action of stably pinching paper or needle, etc. with the finger tips, which is one of the important functions to be realized by humanoid robot hands. In this paper, therefore, the authors firstly propose a small-sized and light-weight robotic hand designed according to the concept of extracting required minimum motor functions and implementing them to the robot, and secondly propose a new robot hand capable of properly realizing a pinching motion with finger tips, by adding the minimum required degree of supplementary freedom which can be realized only with a machine. In the new robot hand, the authors mainly focus on additions of the degrees of freedom of independent motion to the terminal fingers and the degree of freedom of twisting motion to the thumb. Experiments were carried out to investigate force control characteristics of the finger tip joint. The results showed that providing the finger tip with rich force control performance even with weak force is effective for securing delicate control characteristics in a humanoid robot hand.

**Key words**— humanoid robot hand, pinching and grasping, addition of degree of freedom to finger tip, twisting mechanism of thumb.

## I. INTRODUCTION

Various types of robot systems have been developed aiming at realization of cooperative and coexistence with men, being capable of executing complicated works in good cooperation with men in the working and living spaces. Since the first bipedal walking humanoid robot P2 was developed by Honda, Japan in December 1996, then P3 and ASIMO by Honda, WABIAN by Waseda University, SDR-3X and SDR-4X by SONY, H6 and H7 by Tokyo University, HOAP by Fujitsu Limited, and HRP-2P by HRP project were introduced one after another. It may be said that especially walking capability of the robot has reached tentative perfection.

To allow smooth actions in the human cooperative and coexistence environments and transmission of information, almost all systems shown above are equipped with two arms as well as two legs for movement, and visual and audio equipment

Kiyoshi Hoshino is now with University of Tsukuba, and Japan Science & Technology Agency, Tsukuba, Ibaraki 305-8573, Japan (corresponding author to provide phone and fax: +81.(0)29.853.5253; e-mail: hoshino@esys.tsukuba.ac.jp).

Ichiro Kawabuchi is now with TechExperts, Inc., Ohta-ku, Tokyo 143-0015, Japan (e-mail: ichiro\_kawabuchi@post.pioneer.co.jp).

such as a camera or a microphone. However, functions of the hands are limited mostly to grasping and holding an object article, and pushing up and down a lever. Compared with walking skill, the degree of freedom assigned to manipulation functions and to fingers is extremely low. A robot with four-fingers each having three-degrees of freedom, for example, has been developed for high-performance remote manipulation, but manipulation technique is still in underdevelopment stage. Even the more, their appearance is different from five fingers of the human being and their weight is in some cases two times heavier. Realization of robotic hands equipped with functions well suited for practical use is highly expected.

Successful coupling of the robotic hand that realizes functions of the human fingers at higher level with humanoid having size and weight comparable to those of human being has not been reported yet. This is attributable primarily to that if mobility performances comparable to human being are introduced to design target of the humanoid robotic hand, and motors and reduction gears available at present are used, the robotic hand itself tends to become larger and heavier, and it is hardly possible for the robot arm that is designed to be slender and light-weight to hold the hand at its tip. In the case the hand should solely be made small and light, one option is to locate the power source outside the hand and to convey its power to fingertip via a link or a wire [1]-[2]. However, this option does not meet with small-sized and light-weight requirements as a whole system since a large power transmission mechanism is necessary.

Accordingly, in this study, a small-sized and light-weight robotic hand for realization of humanoid was firstly developed according to the policy that required minimum motor functions be extracted and provided. Then, a new robot hand capable of properly realizing a pinching motion with finger tips was secondly developed by adding the minimum required degree of supplementary freedom which can be realized only with a machine. Finally, experiments were carried out to investigate force control characteristics of the finger tip joint.

## II. COMPOSITION OF ROBOTIC HAND (TYPE 1)

### A. Required specifications

Table 1 shows required specifications of this system. Basic specifications targeted here include shapes and motor functions nearly identical with those of human fingers, construction and mass nearly identical with those of adult hands, and size corresponding to smallish hands. The construction and mass referred to here include mechanical elements for composition of the basic mechanism such as motor with encoder and reduction gear and do not include electric

instrumentation system such as motor control amplifier, additive sensors, and connection cable for connection with outside. Since a space for mechanism for driving of rotational motion is required around the wrist joint, a length from fingertip to finger root is set to less than 185 mm from which said space is already deducted.

### B. Arrangement of active joints

A motor with encoder and reduction gear occupies mechanism space of the robotic hand with most non-compromising manner. In order to attain small-sized and light-weight features of the mechanism substantially, these equipment should be reduced as much as possible. The following description shows arrangement of required minimum active joints which satisfy the third required specification.

Four fingers except for the thumb have three joints referred to as MP joint, PIP joint, and DIP joint. MP ( $J_{n,0}$  and  $J_{n,1}$ ) has two degrees of freedom for bending and stretching, and abduction functions of the finger while PIP ( $J_{n,2}$ ) and DIP ( $J_{n,3}$ ) have one degree of freedom respectively for bending and stretching of the finger. Since human PIP and DIP move together in many cases, majority of robotic hands are designed in that these two joints are linked by one motor [3]. In this system, this concept is further developed to that at bending and stretching, all three joints - MP, PIP and DIP - are moved together as being interlocked. Although this design has such a disadvantage that direction of fingertip force can not be changed when grasping an article, it is considered that there is no practical problem in capability of reproducing ordinary grasping status and in majority of expressions by sign language except for difficulty in grasping an article by fingertips.

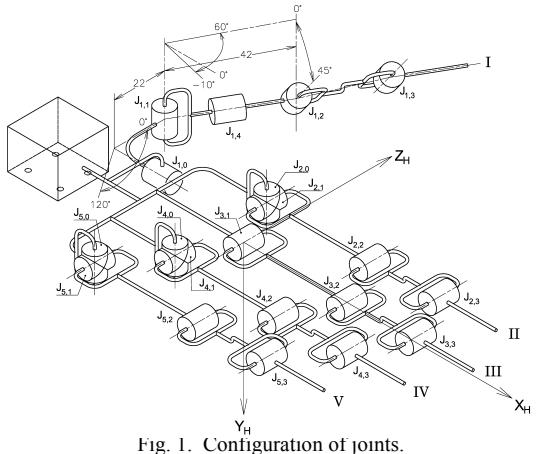


Fig. 1. Configuration of joints.

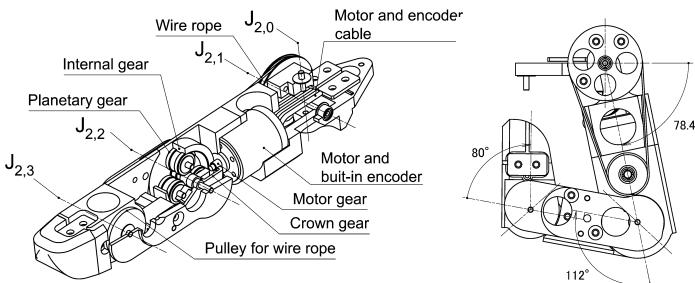


Fig. 2. Mechanism of a finger joint.

Fig. 3. Maximum range of bending.

Table 1 Required specifications

1. To be equipped with shape and motor functions similar to those of humans.
2. Mass of the construction should be less than 500g and length from fingertip to wrist root should be less than 185 mm.
3. To be capable of holding the body and presenting gestures by signal language. More precisely, flexion functions of each finger, opposing function to face the thumb against other fingers, and opening/closing (abduction) of four fingers other than the thumb should be available. Further, movable range of each finger should be sufficient. For example, clasping of five fingers should be possible and a ring should be formed by the thumb and each of other four fingers.
4. There should be a sufficient space at fingertip and palm inside for embedding a force sensor or control circuit.
5. After satisfying above requirements, the motor with maximum possible size and the reduction gear with sturdy construction should be capable of being incorporated.

Likewise, four fingers are interlocked for MP motion used for abduction from viewpoints that no problem is observed in motion reproduction capability. The middle finger is fixed to the palm since this finger is not moved significantly at abduction with regard to the palm.

The thumb has three joints each referred to from the root as CM joint, MP joint, and IP joint. MP and IP are linked in many cases, and CM has two-degrees of freedom. In this system, therefore, two-degrees of freedom is given to CM and one-degree of freedom is given to linking of MP and IP. Although human CM is of saddle joint with complicated shape, this type is reproduced by series arrangement of two revolving joints since substitution of this joint by a small mechanism is difficult.

Based on discussions mentioned above, this system is designed to have degrees of freedom of eight. Fig.1 shows configuration of joints corresponding to one-degree of freedom.

### C. Flexion mechanism of fingers

One of the outstanding problems in developing finger mechanism is how to design mechanism of MP joint with reasonable manner in four fingers except for the thumb where two rotating axes are crossed. One motor and one encoder are mounted to the finger mechanism which means that a total of six wires should be passed through this joint; at least two for the motor and four for the encoder. In order that wires may not be stretched excessively due to a large rotation of the joint, it is ideal that route of wires passes through the intersection of two axes. Therefore, the reduction gear is not placed in the root joint and space for wirings is provided around the intersection of two axes. It is designed in such that rotational power for two axes is given externally via wires and link mechanism.

Fig.2 shows internal construction of the index finger. Other three fingers have the same construction. DC core-less motor with encoder (Faulhaber, model 1516R mini-motor,

maximum output 0.52 W) which is the largest model is built into the coax connecting two joints MP and PIP. The reduction gear is incorporated in PIP to drive this joint. There are three reasons why the reduction gear is provided here. First, its outer shape is the second largest next to MIP and space for incorporation is made available easily. Second, power transmission route to the driven joint becomes the shortest which is effective for prevention of bad effects such as generation of a play or reduction in rigidity. Third, of three joints being linked, PIP has the largest rotating angle which means that the transmission mechanism to the driven joint develops speed reducing and power increasing effects and is advantageous for powerful and stable driving.

The reduction gear is designed to be of crown gear plus three-stage planet gear mechanism. As for optimum type of motor incorporation, motor shaft is arranged parallel with axis of the finger and therefore, motor rotating axis is orthogonal to the joint axis. In general, with gear mechanism for axes orthogonal each other, rigidity is low and a play is generated easily. Therefore, orthogonal power is taken out using crown gear from the first stage looking from the motor so that bad effects may appear least in the joint output. Reduction gear ratio used in this system is 1/350 and the maximum joint torque is 5.5 kgf-cm.

Wire-pulley mechanism is adopted for the power transmission mechanism, and shape of the pulley is carved at the side of the finger. Since this mechanism is arranged thinly on the side of the finger, it is possible to use sizable space of mechanism interior from PIP to tip freely for incorporation of sensors and electric instrument parts. Although identical transmission mechanism can be constructed by link mechanism, it tends to become larger due to restrictions on mechanism arrangement to facilitate smooth transmission of rotational angle of approximately 90 degrees. Therefore, this transmission mechanism was not adopted. Ratio of transmission of the wire-pulley mechanism is 7/10 for from PIP to MP and 5/7 for from PIP to DIP.

Fig.3 shows maximum bending condition. It is noticed from this that sufficient movable range is secured. Two active joints with this reduction gear are arranged in compact fashion at the root of the thumb. This configuration resulted in a sufficient movable range where a ring can be formed by the thumb and the fourth finger as shown in Fig.4. While the motor is idle turning, it is possible to cause a light passive movement without causing a play by giving a force of several tens gf to the fingertip.

#### D. Abduction-adduction mechanism

For linking mechanism for the index finger, annular finger and fourth finger, link mechanism is adopted since their rotation angle is small. Fig.5 shows this link mechanism looking from back of the palm and its movable range. Root of the annular finger is driven directly by the motor. In order to obtain a large gear ratio with the smallest possible number of stages of the gear train, a circular gear with maximum possible radius is fixed to the annular finger to be driven by a pinion as shown in Fig.6. Reduction ratio attained by this configuration is 1/400. The driving motor is moved to outer edge of the palm utilizing distance of radius of the circular gear effectively.

Nearly half of space in the palm can now be utilized as the space for electric instrumentation. Even under the condition where each finger is bent to the maximum degree as shown in Fig.3, abduction movement can remain independent by securing a clearance between the fingertip and the palm. Scissors gesture (paper-rock-scissors) or the like can be reproduced.

### III. PINCHING WITH FINGER TIPS (TYPE 2)

#### A. Concept

One of important functions expected of a humanoid robot hand is a function of gently picking up something small, thin or fragile, namely putting only the tip of fingers in contact with the object. When using such robot as a supporting system for human beings in the living environments of modern people, the function of minutely picking up things is believed to be equally as or even more important than the function of grasping a heavy object securely, nothing but putting portions other than finger tip such as palm, etc. in contact with the object. However, putting this function into practice is more difficult than putting into practice the grasping function, and is delayed, due to existence of the following two problems:

One is that, to construct a humanoid robot hand in a size and a shape close to those of the humans, the degree of freedom of motion to be furnished on the robot should be sacrificed to some extent [4]. The reason for it is that, since electric motor is the only proper actuator currently available, the degree of freedom of motion to be expected of a humanoid robot hand sharply drops compared with that of the humans, considering the number of motors and reduction gears which can be incorporated in the hand. The second point is difficulty of realizing a drive mechanism with excellent force controlling performance for achieving a delicate control of finger tip. The reason for it is that, while there is no choice but use small motor for loading as many motors as possible and it becomes necessary to increase the reduction ratio of the reduction gear to extract a large torque from small motors, it deteriorates the force controlling performance by increasing the play and friction loss of the drive mechanism.

Now, an orthodox method for solving such problems is to promote achievement of high output, high efficiency, compact size and light weight of the mechanical elements such as motor, reduction gear, etc. However, even with the use of mechanical elements of highest class currently available, it is believed far from full solution of the problems. Moreover, the work for achieving high performance of the mechanical elements themselves is out of the scope of our activities.

For that reason, in this chapter, the authors investigated a proper and new form, from a new viewpoint apart from the orthodox method, by allowing to add some motional functions realizable only with a machine, while bearing in mind the basic principle of not destroying the general harmony as a form of humanoid robot. And, we proposed the minimum required degree of freedom to be added, a method for securing compatibility between delicate pinching function and powerful grasping function, as well as concrete mechanisms for achieving it, and developed a new humanoid robot hand.

### B. Addition of degree of freedom of independent motion to the terminal finger

The finger mechanism of our humanoid robot hand is composed of four joints, called “terminal joint”, “middle joint”, “base joint” and “midhand joint” in order from the finger tip, in the same way as on a human hand. The midhand joint refers literally to the basic portion positioned inside the palm. The common structure of the finger mechanism of the second to fourth fingers is indicated in Fig.7. The joint numbers given in the figure will hereinafter be used for the explanation of the second to fourth fingers. For the first finger (thumb) which has a structure slightly different from that of other four fingers, an explanation of its concrete structure will be made later separately.

The four joints  $J_{n,0}$  through  $J_{n,3}$  are driven for making expansion and contraction of fingers and open/close motions between fingers. Here, the drive mechanism of  $J_{n,0}$ ,  $J_{n,1}$ ,  $J_{n,2}$  requires a large torque capacity which may well be said to be a heavy burden on a small motor which can be loaded on a robot hand, because of a large mass of the finger mechanism to be supported. And, there is a limit to the resolution of the produced torque, as general characteristic of a drive mechanism, and it is rather difficult to generate for the drive mechanism of  $J_{n,0}$ ,  $J_{n,1}$ ,  $J_{n,2}$  to stably produce a fine finger tip force. On the other hand, the drive mechanism of  $J_{n,3}$  which supports only a small and light terminal mass requires a small torque capacity, and can therefore produce a fine finger tip force comparatively easily. It also has an advantage that the transmission loss of force from the drive mechanism of  $J_{n,3}$  to the finger tip is zero, and is therefore an optimal drive mechanism to be provided with a function of producing a fine finger tip force.

However, on humanoid robot hands developed generally is adopted a system by which  $J_{n,2}$  and  $J_{n,3}$  are driven in linkage by a common motor in a way to simulate the motional function of a human hand. It is also a system adopted out of necessity, because no strong finger tip force necessary for the holding function can be expected, if you realize a  $J_{n,3}$  drive mechanism which can be incorporated in the middle joint of small capacity. Under such circumstances, in the present development, we propose, as a new system different from the conventional one, a system not imposing the function of strongly holding an object on the  $J_{n,3}$  drive mechanism but expecting only production of a fine finger tip force required for delicately picking up an object from it. To be concrete, we will add a small  $J_{n,3}$  drive mechanism built up by giving priority to possibility of incorporation in the middle joint, and realize independent motions and fine control of finger tip force of the terminal joint. Because the first finger will also be provided with functions and structure similar to those of this  $J_{n,3}$  drive mechanism, the name of terminal joint drive mechanism will be used commonly to all the five fingers hereafter.

### C. Structure of terminal drive mechanism

A terminal drive mechanism must have a particularly excellent control performance of small force. It requires, therefore, a high-efficiency reduction gear with low frictional resistance and play. As type of reduction gear, a gear train will be adopted which uses only high-efficiency spur gears capable

of building a fine mechanism because of their simple shape. The length of the motor is restricted to the width of the finger joint, because the motor must be incorporated in such a way that its axis of rotation is parallel to the axis of rotation of the terminal joint. Since the output of such motor is very small, the reduction gear must have a high speed reducing ratio, to obtain an effective torque. However, realizing a high speed reducing ratio by increasing the number of stages of gear train should be avoided, because it leads to deterioration of efficiency and increase of play instead. For that reason, we will build up a two-stage reduction gear of high speed reducing ratio, by reducing the size of the gear module as much as possible and by combining large gears and small gears, while keeping in mind to maximize the speed reducing ratio per stage.

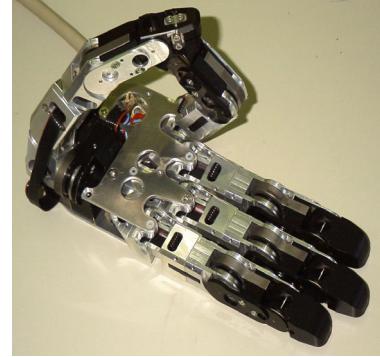


Fig. 4. Contact in thumb and pinky.

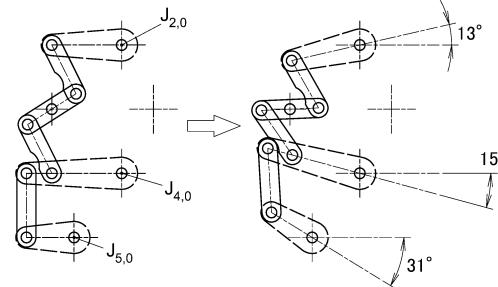


Fig. 5. Linking mechanism in abduction.

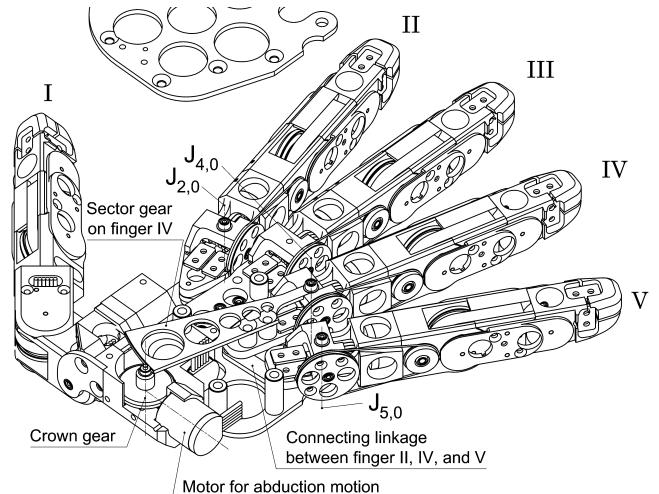


Fig. 6. Inside mechanism in the palm.

Fig.8 indicates an example of concrete structure of a terminal drive mechanism. A pinion is fixed to the motor shaft and is turned. The spur gear 1 engaged with the pinion 1 and the pinion 2 are connected to each other to turn together. Their axis of rotation exists on the middle joint. The spur gear 2 engaged with the pinion 2 is connected with the terminal joint to turn together. We use large spur gears 1, 2 for obtaining a large speed reducing ratio and, by disposing them by the side portion of the finger mechanism, we obtain a margin of space for housing sensor and electrical fixtures, etc. in the finger mechanism. The main features are the following: The number of teeth is set for nine which is the smallest realizable number, and the gear module is made sufficiently small at 0.16. And 3/250 was realized as total speed reducing ratio. Although the maximum torque of the motor is very small at approximately 0.5 Nmm, the maximum finger tip force comes to approximately 2 N, under the effect of this high speed reducing ratio and the effect of a short distance of approximately 0 mm between the joint  $J_{n,3}$  and the finger tip, thus providing a sufficient force for picking up an object. The potentiometer is used for measuring the angular displacement of  $J_{n,3}$ .

#### D. Movable range of rotation of $J_{n,3}$ for compatibility of pinching and grasping

Since the torque produced at the terminal joint drive mechanism is small, it is impossible to transmit a force for power grasping to the object at the finger tip. However, because a mechanical stopper supports the finger tip force at an end in the movable range of rotation of  $J_{n,3}$ , we can realize a power grasping easily, if only we tolerate the defect that the rotational angle of the terminal joint is limited to that position. This system is probably a general method for enabling compatibility of pinching function and grasping function, but this method has a defect that the specially available degree of freedom and high force control function of the terminal joint drive mechanism become invalid at the time of holding. We will therefore propose, in the present development, a new method by which those merits remain effective even at the time of grasping.

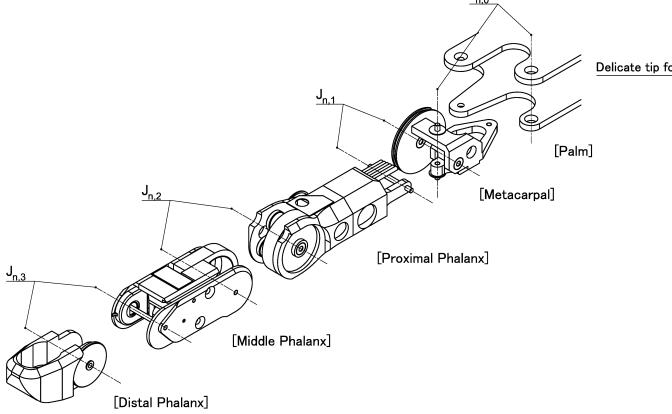


Fig. 7. Joint construction of the finger mechanism of the second to fourth.

A new holding method of this robot hand is shown in Fig. 9. To put it briefly, this method consists in transmitting a grasping force to the object at portions on the middle joint and the base joint, and transmitting only a weak holding force to the object at the finger tip. For that purpose, provide a sufficient margin in the direction in which the finger tip moves away from the object in the movable range of  $J_{n,3}$ . At the same time, arrange the shape of the inside portion of the middle joint and the base joint, to facilitate their contact with the object.

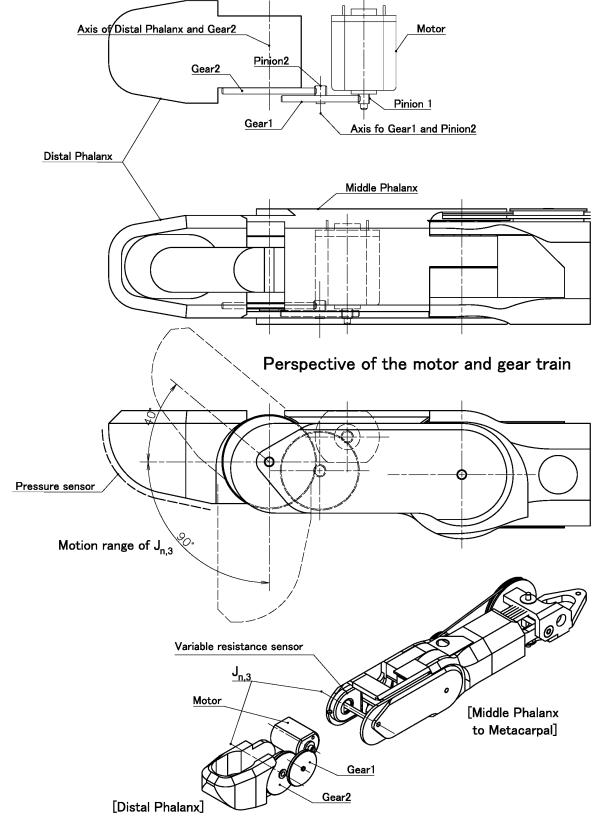


Fig. 8. Structure of terminal drive mechanism, and moving range of rotation of  $J_{n,3}$ . There exists no conventional robot hand having a moving range of rotation in which the finger turns actively to the back side.

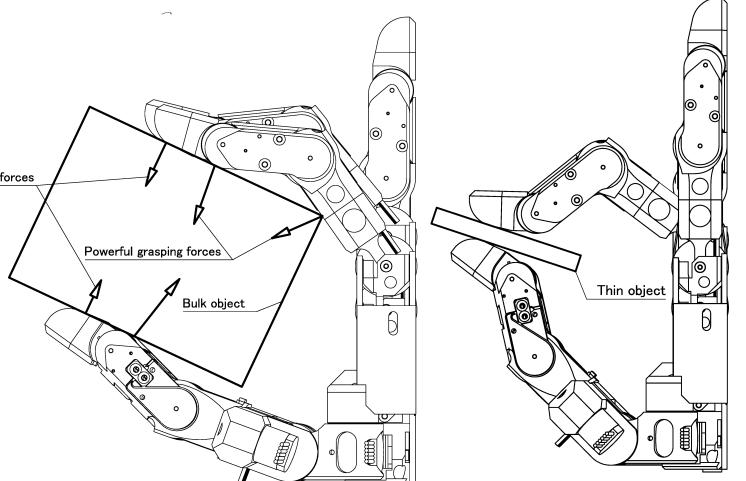


Fig. 9. A new holding method, and two different kinds of contact force.

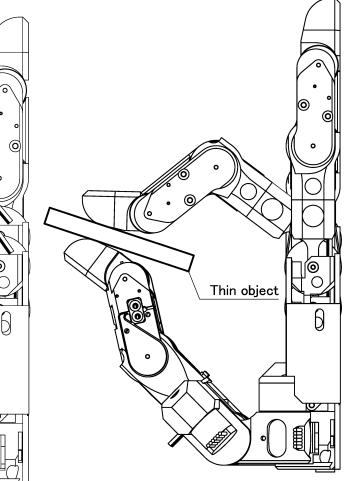


Fig. 10. Pinching by the finger tip of the thumb and middle finger, as an example of picking motion.

The main advantages of this new method are the following: As the acting point of the grasping force moved from the finger tip to portions on the middle joint and the base joint, it becomes possible for the drive mechanism of  $J_{n,0}$ ,  $J_{n,1}$ ,  $J_{n,2}$  to generate a powerful grasping force with the same torque. Since a flexible finger tip force by the terminal joint drive mechanism is added to this holding force, a slip-free pinching becomes easier. Moreover, because the movable range of rotation of  $J_{n,3}$  is widened here, it also provides an effect of stably picking up the object by putting the finger cushion widely in contact with the object, as shown in Fig.10, and is useful.

#### E. Addition of degree of freedom of twisting motion to thumb

When the tip of the thumb and the tip of other fingers of a human hand touch each other face to face, the contact portion between the two is the cushion at finger tip on the thumb, but it is often a position off the finger tip cushion on the part of other fingers. This phenomenon is produced because the thumb does not have any twisting function. A human hand has soft skin and flesh at the finger tip and a high control performance of motion and force at the respective finger tips, and can therefore realize a stable pinching function even if the two groups of finger do not face each other exactly at the cushion part. However, a general robot hand has only a much lower control performance of motion and force compared with a human hand, as mentioned before. The terminal joint drive mechanism introduced previously to solve this problem demonstrates a force control function in one direction only. To fully utilize this capacity, it is desirable that the finger tip force produced by the terminal joint drive mechanism at the tip of the two finger groups face each other justly, namely the two finger tips oppose each other exactly at the cushion. For that reason, we propose to add a twisting function of the thumb, which does not exist on a human hand, to realize the degree of freedom of motion necessary for it. For the sake of comparative reference, Fig.11 indicates an example of a state of grasp in the case where the twisting function of the thumb does not work.

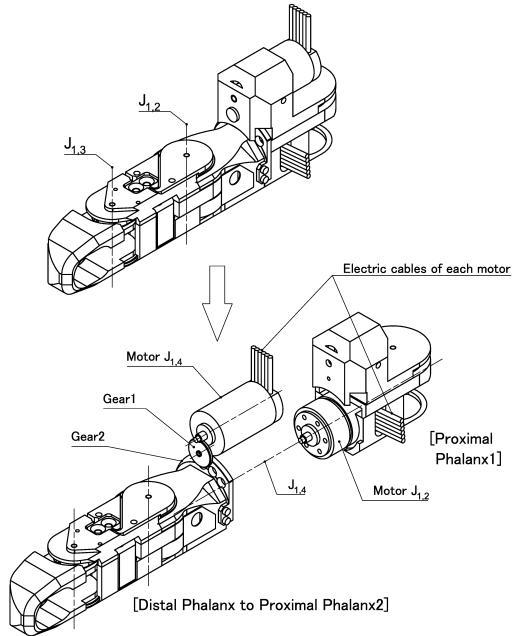


Fig. 13. Structure of twisting mechanism of the thumb.

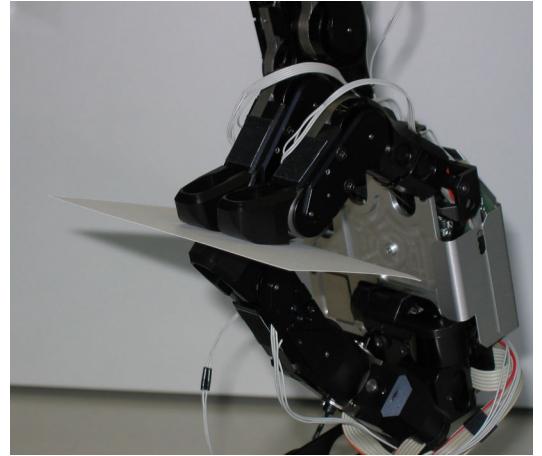


Fig. 14. A robot hand developed in this study.

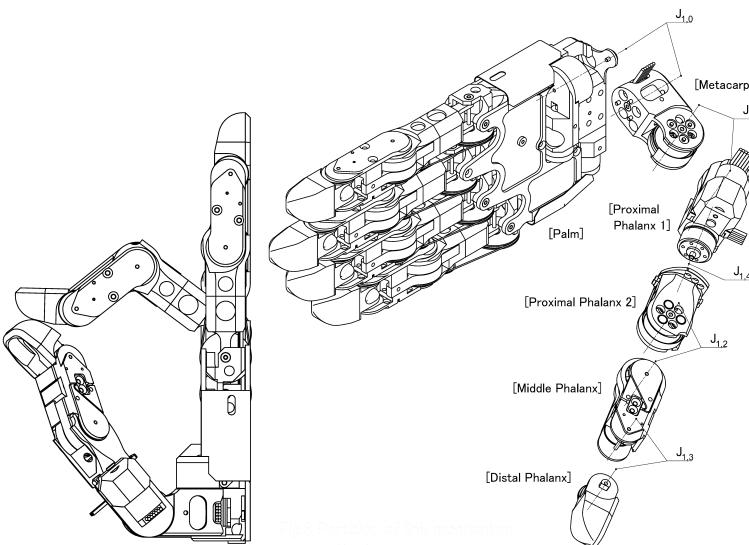


Fig. 11. An example of pinching motion in the case where the twisting function of the thumb does not work.

Fig. 12 Joint construction of the finger mechanism of the thumb.

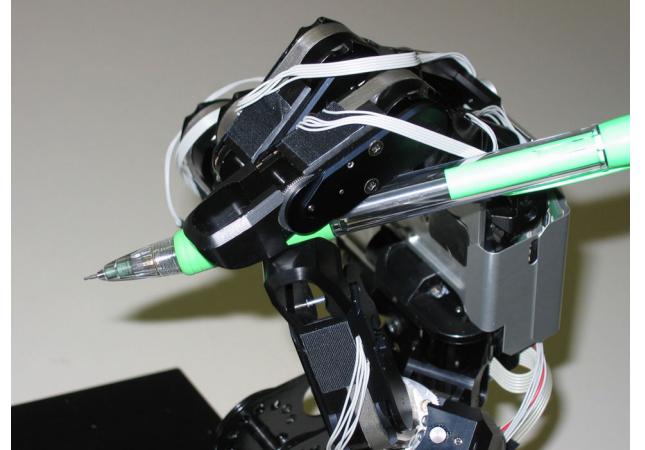


Fig. 15. A robot hand holding a pen for writing characters.

Addition of twisting function of the thumb provides another advantage. In the case where the finger tip cushion of the robot hand is flat like that of a human hand, the stability of pinching motion increases, because it becomes possible to pick up an object by pressing the entire face of the cushion. The effectiveness of the robot further improves, if it is equipped with a lightweight and thin pressure sensor for measuring the pressure distribution on the finger tip cushion.

#### F. Structure of twisting mechanism of thumb

Fig.12 indicates the structure of a new twisting mechanism of the thumb. The joints will be named as “terminal joint”, “middle joint”, “first base joint”, “second base joint” and “midhand joint” in order from the finger tip. A robot is provided with two joints  $J_{1,0}$ ,  $J_{1,1}$  at the root, simulating the two degrees of freedom at the root of the thumb of a human hand, but that is not enough for making the tip of the thumb and the tip of other fingers touch each other correctly at the cushion part. For that reason, the base joint which ought to be integral on a human hand will be split into two parts, and a new joint  $J_{1,4}$  will be inserted between them. To construct the joint  $J_{1,4}$  in the smallest possible size, the cylindrical case of the joint  $J_{1,2}$  drive motor incorporated over the base joint 1 to the base joint 2 will be diverted as shaft of  $J_{1,4}$ . The function of the remaining joints  $J_{1,2}$ ,  $J_{1,3}$  is the same as that of the other four fingers.

Fig.13 indicates an example of concrete structure of the twisting mechanism of thumb. Unlike a terminal drive mechanism, this twisting mechanism requires a large motor for putting the large mass of finger mechanism itself in motion. Therefore, a bulge was supplemented to the base joint 1 to incorporate a large motor in it. To increase the efficiency of the speed reducing mechanism, we reduce the size of the gear module as much as possible, in the same way as the terminal drive mechanism, and combined large gears and small gears, to constitute a two-stage reduction gear with a high speed reducing ratio. A pinion is fixed to the motor shaft and is turned. The spur gear 1 engaged with the pinion 1, and the pinion 2 are connected to each other to turn together. Their axis of rotation exists on the middle joint. The spur gear 2 engaged with the pinion is connected with the base joint 2 to turn together.

Fig.14 and Fig.15 show a small-type and light weight robot hand for humanoid developed by the author's group in this study, satisfying the mechanisms mentioned above.

## IV. EVALUATION OF FORCE CONTROL CHARACTERISTICS

### A. Force control with force sensor

Experiments were conducted to investigate force control characteristics of the joint  $J_{n,3}$  at finger tip. The method of testing is the following: A positional control order in the shape of sine wave was given to a motor driving joints  $J_{n,1}$  and  $J_{n,2}$  in linkage, to make a motion of hitting the finger tip against the base. At the same time, to prevent the contact force between the finger tip and the base from exceeding a certain limit value, we controlled the force of the joint  $J_{n,3}$ . The finger tip contact force used for controlling the force of the joint  $J_{n,3}$  was measured by means of a film-like force sensor (FlexiForce of Nitta



Fig. 16. Scene of experiment of force control.

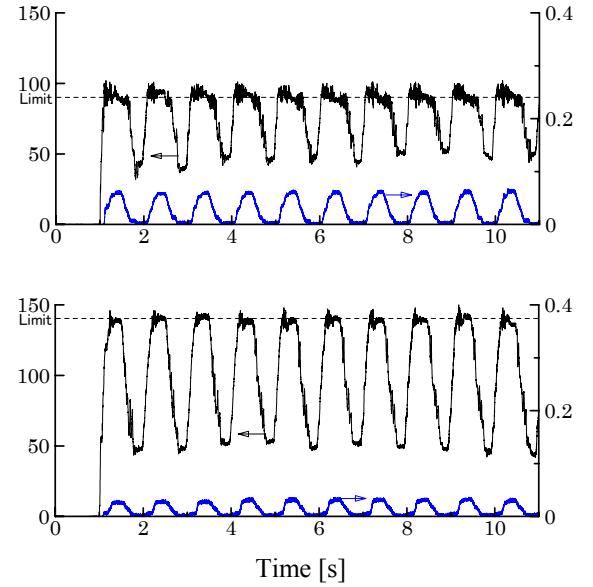


Fig. 17. Evolution of force produced at finger tip and angular displacement of finger tip. The upper stage indicates the results of the case with a limit force of 90 gf, and the lower stage in the case with a limit force of 140 gf.

Corporation, type with maximum measured value 4.4N) pasted on the base. Fig.16 indicates a scene of experiment.

About the evolution of force generated at the finger tip and of angular displacement of the joint  $J_{n,3}$ , Fig.17 indicates the results of experiment in the case where the limit value is set for 90 gf and 140 gf. The finger tip and the base collided with each other at the one second time, and the contact state was maintained thereafter. We could confirm that a force control for preventing the contact force from exceeding the critical value functions in the case with a limit value of both 90 gf and 140 gf, enabling the joint  $J_{n,3}$  to work smoothly. The larger angular displacement of the joint  $J_{n,3}$  in the case with a limit value of both 90 gf than that in the case of 140 gf is attributed to an action of moving more largely and relaxing a larger force.

From those test results, the authors conclude that providing the finger tip with a joint rich in force control performance even with weak maximum generated force is effective for securing delicate control characteristics finger tip force.

### B. Performances

Then the authors carried out the experiment which confirms the practicability of our robot hand mechanism. The handling of a business card and holding of a pen which need the complicated motion of the thumb were selected as representative examples of the robot hand movement. The force sensor was not attached to the finger tips in this experiment, because the development of force sensor for the finger tip is not our purpose, nor useful force sensors for the finger tip is not practically available these days. We just adopted, therefore, the force control where the torque of each motors was controlled according to the open-loop without using advanced sensors and control algorithms.

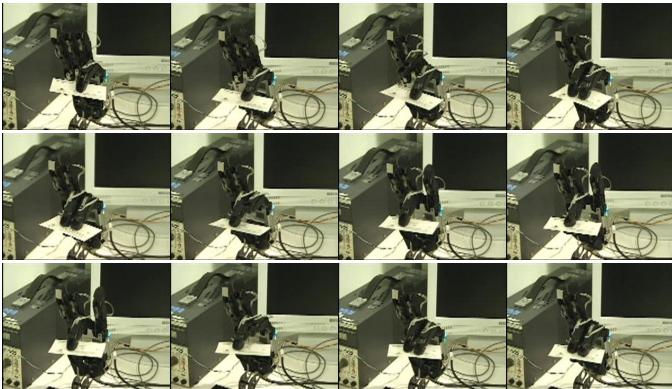


Fig. 18. Snap shots of robot hand handling a business card.

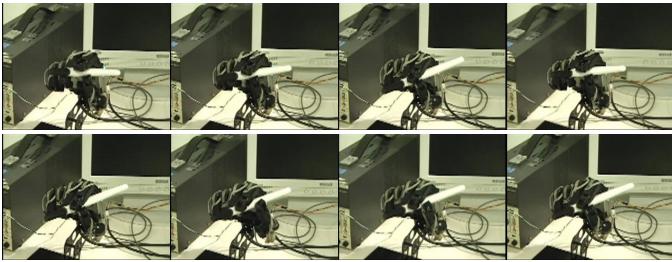


Fig. 19. Snap shots of robot hand holding a pen stably.

As pinching motion of a business card, the robot hand was forced to softly touch and slip on the surfaces of both right and reverse sides of the business card, which may be a difficult task for conventional robot hands. A series of the motions were as follows:

- (1) pinching of the center of the card with the thumb and index finger,
- (2) adjoining the middle finger to the index finger, and pinching with the thumb, index and middle fingers,
- (3) slipping of the thumb on the back surface of the card, and positioning it to the opposite side of middle finger,
- (4) separating the index finger from the business card,
- (5) adjoining the index finger to the middle finger, then, pinching the card with the thumb, index and middle fingers again,
- (6) slipping of the thumb on the back surface of the card, and positioning it to the opposite side of index finger,
- (7) separating the middle finger,
- (8) return to (1).

Fig.18 show the snap shots of the performance of the robot hand as the results of experiments. Our robot hand repeatedly performed the series of the movement mentioned above, pinching the business card stably.

As holding motion of a pen, the robot hand was forced to slip the tip of the thumb on the side surface of the pen, with stable holding. This performance is needed for holding a pen again and changing the way of retaining in a right way, for example, to pick up a pen from a pencil box. As was shown in Fig.19, the performances and experimental results of the robot hand indicate that the mechanism of the hand is proper and sufficient for delicate force control at the finger tips.

## V. CONCLUSION

It is difficult to generate the action of stably pinching paper or needle, etc. with the finger tips, which is one of the important functions to be realized by humanoid robot hands. In this paper, the authors firstly propose a small-sized and light-weight robotic hand designed according to the concept of extracting required minimum motor functions and implementing them to the robot, and secondly propose a new robot hand capable of properly realizing a pinching motion with finger tips, by adding the minimum required degree of supplementary freedom which can be realized only with a machine. In the new robot hand, the authors mainly focus on additions of the degrees of freedom of independent motion to the terminal fingers and the degree of freedom of twisting motion to the thumb. Experiments were carried out to investigate force control characteristics of the finger tip joint. The results showed that providing the finger tip with a joint rich in force control performance even with weak maximum generated force is effective for securing delicate control characteristics finger tip force.

## REFERENCES

- [1] S. C. Jacobsen, J. E. Wood, D. F. Knutti and K. B. Biggers, "The UTAH/M.I.T Dextrous Hand: Work in Progress," *Intl. J. of Robotics Research*, 3, 4, pp.21-50, 1984.
- [2] Shadow Dextrous Hand: <http://www.shadow.org.uk/products/newhand.shtml>

- [3] Gifu Hand: <http://www.kk-dainichi.co.jp/>
- [4] <http://www.robotic.dlr.de/mechatronics/hand/>