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Five-fingered Robot Hand using Ultrasonic Motors and Elastic Elements*

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***Abstract* - A five-fingered robot hand having almost an equal number of DOF to the human hand is developed. The robot hand is driven by a unique method using ultrasonic motors and elastic elements. The method makes use of restoring force as driving power in grasping objects, which enables the hand to perform stable and compliant grasping motion without power supply. In addition, all the components are placed inside the hand because the ultrasonic motors have characteristics of high torque at low speed and compact size. Applying the driving method to a multi-DOF mechanism, a five-fingered robot hand is designed. The robot hand has twenty joints and DOF. It is almost equal in size to the hand of an average grown-up man. The robot hand is produced, and control experiments are conducted. As a result, the potential of the robot hand is confirmed.**

Index Terms –Robot hand, Ultrasonic motor, Tele-operation, Wire-driven mechanism

I. Introduction

Until now, human beings have been developing a variety of robot hands imitating human hands for taking human operation [1]-[10]. The robot hands that have the advanced function are useful as the end effecters. They can be applied in various fields, such as tele-operation with master-slave system. However, it is not enough to reproduce the motion of the human hand, because the conventional robot hands have problems in respect of degree of freedom and versatility. Therefore, a five-fingered robot hand having size, shape, and number of DOF equal to the human hand is developed in this research. The robot hand is driven by a unique method using ultrasonic motors and elastic elements. This method provides flexible, stable and efficient motion to the robot hand. In previous research, we developed index robot finger, and the position control experiment was conducted [11]. This paper describes the design, manufacturing and the control experiment of the robot hand, and we confirm the potential of the developed robot hand.

II. Design

A. Basic Design

By imitating the structure of a human hand, the robot hand can realize various grasping, and handling motion that were adapted for life environment, and intuitive operation is possible for operator. Thus the size, shape and DOF of the robot hand are design to be equal to that of human hand.

In this research, we divided robot hands into two types; built-in actuator type and external actuator type. Built-in actuator type of robot hands generates the motion of fingers by using motors installed inside the finger or palm. This type of robot hand drives the joint by direct drive or gear drive. External actuator type makes the structures of its fingers simple and light by using wire or belt driving mechanism.

In the case of built-in actuator type [1]-[4], this type of robot hand has merit that the hand can be used with various types of robot arms because the robot hand has the independent structure. However, there are some demerits. The most serious one is the limitation of size. This type must install all mechanical elements, such as the actuator and the sensor, inside the finger or the palm, thus it is difficult to develop the robot hand with DOF equal to a human hand. On the other hand, in the case of external actuator type [5]-[7], multi DOF motion is possible for this type because the restrictions on internal structure are reduced by using a wire or belt-driven mechanism. However, since this type of hand must be mechanically connected to external actuators, it is difficult to use with various robot arms.

In this research, we take advantage of the merits of both types of robot hands in designing our robot hand. In order to set all actuators inside the palm, we adopt the ultrasonic motor as the actuator. In addition, the robot hand has the independent structure with five fingers. Design limitation of finger part is alleviated by a wire-driven mechanism. As a result, the robot hand that has 20 DOF, and almost same form as a human hand is designed.

The ultrasonic motor has features such as high driving torque at low rotational speed, compact size and light-weight. Therefore it is suitable for the actuator of robot hand that has structural restrictions. Furthermore, rapid response and silent motion of the ultrasonic motor are advantages in order to develop a robot hand. However, because the ultrasonic motor has high driving torque, there is the risk that the hand and the object will break when they make contact. It is difficult for us to control the torque of ultrasonic motor because of its non-linearity characteristic. In the next part, we proposed a novel wire driving method using elastic elements to solve these problems in order to realize efficient, flexible and stable grip operation.

B. Driving Methodology

A five-fingered robot hand is driven by the method using ultrasonic motor and elastic elements. The outline of

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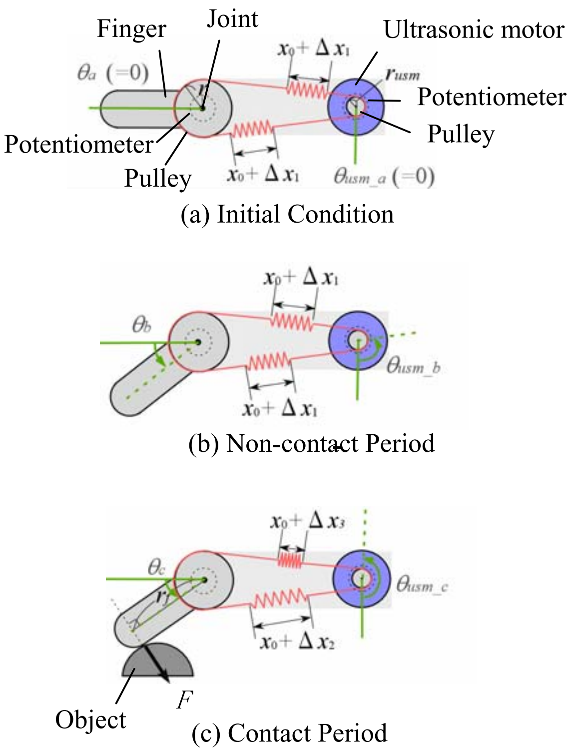


(a) Initial Condition

(b) Non-contact Period

(c) Contact Period

Fig. 1 Outline of driving method

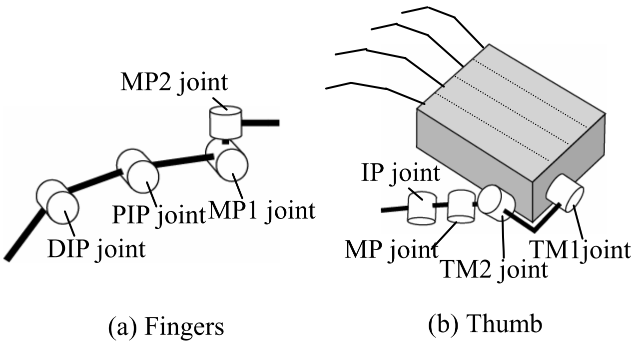
driving method is shown in Fig. 1. The characteristic of the driving method is the use of two elastic elements within a wire. Both ends of the wire are connected to the pulley. Rotation angle of ultrasonic motor and joint angle are measured by two potentiometers.

At the initial state shown in Fig. 1(a), two elastic elements are stretched from initial length x_0 to ($x_0+\Delta x_1$). The restoring force of wire is expressed as $k\cdot\Delta x_1$, where k is the spring coefficient of the elastic elements. Therefore, restoring force of wire is controlled by changing initial deformation of the elastic elements. In addition, elasticity of the elastic elements provides passive compliance to each joint. The elasticity of the joint is controlled by changing the spring coefficient of the elastic elements. With mechanical compliance, the robot-hand would obtain high stability against the impact of collision.

Each joint rotates in the same direction as the connected ultrasonic motor. During the non-contact period shown in Fig. 1(b), position control of a finger is performed by controlling the rotation angle of ultrasonic motor with the feedback of joint angle. When the inertia of the finger is small enough to ignore the deformation of elastic element, the relationship between rotation angle of ultrasonic motor and joint angle is expressed as

$$r\cdot\theta_b = r_{usm}\cdot\theta_{usm\_b} \tag{1}$$

When the finger is in contact with an object, deformation of elastic element changes the relationship shown in equation (1), thus a contact condition can be detected. During the contact period shown in Fig. 1(c), the force F generated by the difference of restoring force of two elastic elements is



(a) Fingers

(b) Thumb

Fig. 2 Arrangement of DOF

applied on an object. The torque τ and the force F would be expressed as

$$\begin{aligned}\tau &= F\,r_f \\ &= 2\,k\,r\,(\,r_{usm}\,\theta_{usm\_c} - r\,\theta_c) \\ &= 2\,k\,r\,r_{usm}\,(\,\theta_{usm\_c} - \theta_c\,r/\,r_{usm}) \\ &= 2\,k\,r\,r_{usm}\,\Delta\theta_E\end{aligned} \tag{2}$$

where, $\Delta\theta_E$ is the amount of angular deformation of the elastic element, which will be the handling parameter for force control described in section IV *C*. By assigning the rotation angle measured with potentiometer to equation (2), force F can be calculated at the contact period. Therefore, this driving mechanism does not require any force sensors or torque sensors, which will help simplify the system.

Furthermore, equation (2) shows that force control is possible by controlling the rotation angle of ultrasonic motor. As already stated, ultrasonic motors have difficulty in torque control, however, it does not require reduction gears, and need no electric power to stay stationary. Therefore, ultrasonic motors are suitable for precise position control. This driving mechanism utilizes these characteristics of ultrasonic motor, and achieves highly accurate force control.

If electricity applied to ultrasonic motor is stopped at the contact period shown in Fig. 1 (c), restraining torque of the ultrasonic motor keeps the length of elastic element, and force F is continually applied to an object. Thus, by using restoring force as the output force, this driving mechanism achieves stable and efficient grasping motion in tasks that require constant grasping force.

C. *Driving Mechanism*

The driving mechanism of a five-fingered robot hand with twenty DOF is stated in this paragraph. The index finger, middle finger, ring finger and little finger are designed with the identical driving mechanism, which is shown in Fig. 2(a). The placement and appellation of each joint correspond to those of a human finger. With the assumption of use of ring-shaped ultrasonic motor, driving mechanism for four DOF finger shown in Fig. 3 was designed. Ultrasonic motor 1, 2 and 3 produce driving force for MP1, PIP and DIP joints. Ultrasonic motor 4, which produces driving force for MP2, is placed on top of ultrasonic motor 3. Previously stated driving mechanism is applied to each joint.

For the thumb, application of a human finger's mechanism was difficult. However, by setting DOF as

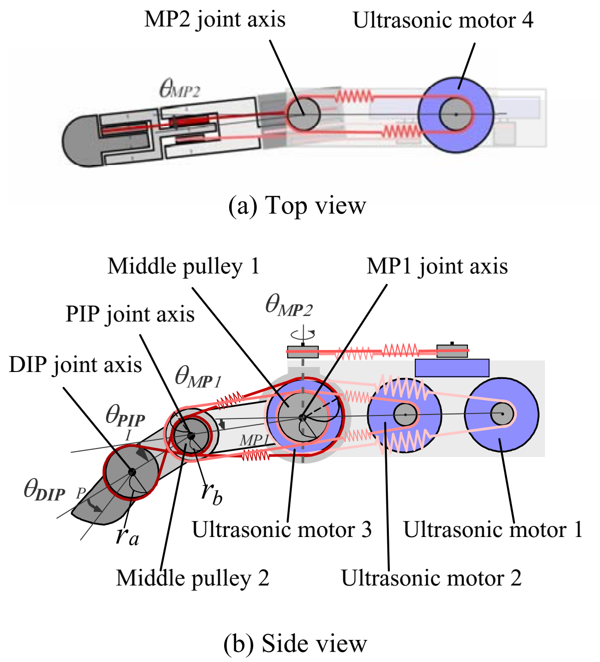


Fig. 3 Outline of driving mechanism of fingers

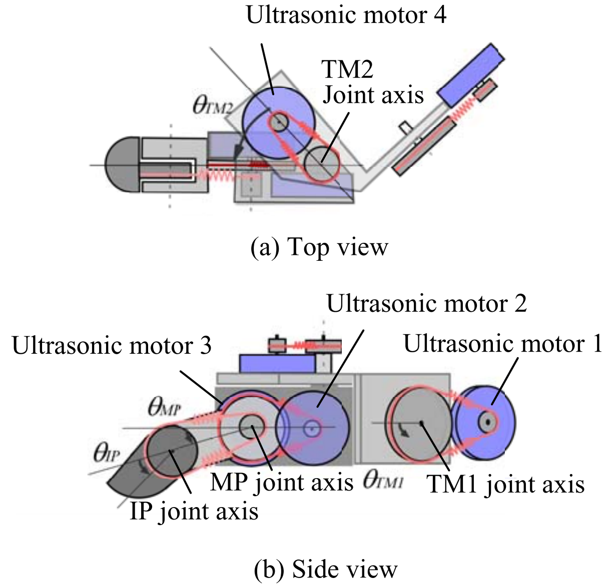


Fig. 4 Outline of driving mechanism of thumb

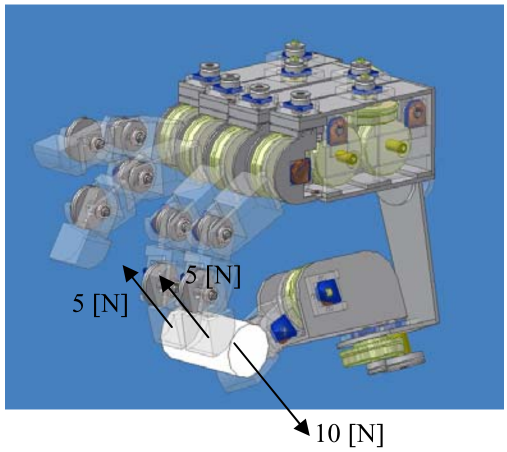


Fig. 5 Reaction force of robot fingers

Fig. 6 Developed five-fingered robot hand

shown in Fig. 2(b), the thumb became capable for executing approximate human thumb motion. Motion of the TM1 joint enables thumb to face other fingers. In addition, the torque required at the bottom joint to produce force at the fingertip is small compared to the other finger of which the DOF placement is shown in Fig. 2(a). Therefore, the thumb can produce more force at the fingertip compare to other fingers. Fig. 4 shows the designed driving mechanism of a five-fingered robot hand. Each finger contains four DOF with the previously stated driving methodology. Ultrasonic motors 1, 2, 3 and 4 produce driving forces for TM1, MP, IP, and TM2 joint.

D. Detailed Design

Based on the driving method mentioned above, detailed design of a five-fingered robot hand was achieved. The size of each section is decided in accordance of the average size of a Japanese grown-up man's hand. The range of motion of each joint is also equal to a human hand. As for the fingertip force, based on the state of precision grasp of a cylinder with a diameter of 25mm as shown in Fig. 5, the diameter of each pulley was decided so that the index finger and middle finger can apply 5N force to the cylinder, and the thumb can apply 10N force to the cylinder. Ring finger and little finger are also designed so that they can apply force of 5N at the fingertip.

III. Implementation

Based on the detail design, a five-fingered robot hand was implemented. The exterior of the hand is shown in Fig. 6. We used USR30-B4 (maximum output torque: 0.1Nm)

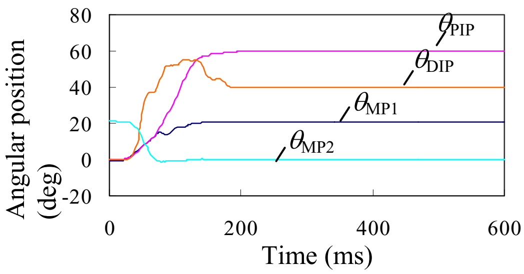


Fig. 7 Step response of robot index finger

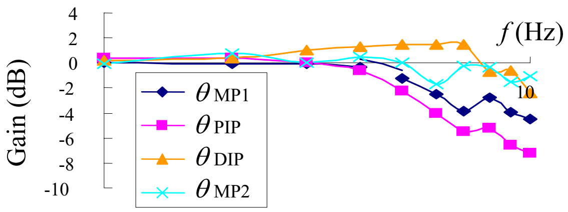


Fig. 8 Frequency response of robot index finger

made by "Sinsei-Kogyo" as actuator. As the angle sensor, trimmer potentiometer PVS1-103A01 made by "Murata Seisakujo" was used. As the elastic element, a coil-spring was considered the best. However, considering the problem of limited space, the setting of coil-springs was difficult. Therefore, material having small elasticity was used as the wire to realize a function of the wire and the elastic element. Considering strength and elasticity, a nylon string was applied as wire. Based on the result of a tension test, a nylon string of each finger was designed so that a maximum output torque of motor of each joint creates enough deformation of nylon string to measure.

The mass of entire hand is 853g, which is light compare with other robot hands. Width of the palm is 86mm, the length from fingertip to wrist is 203mm, the length from fingertip of thumb to fingertip of little finger is 190mm. Therefore the robot hand that has almost the same size of human hand is realized.

A control system of this hand is implemented. To import the output of potentiometer, the AD converter was used. For instruction to the ultrasonic motor driver, the DIO board was used to command the direction of rotation, and the DA converter is used to command the rotation speed. Using this control system, control experiments were conducted for evaluation of the implemented robot hand.

IV. Control Experiment

A. *Step Response*

First, step response is measured with the index finger of developed robot hand. Initial state of joint angle is 0 degree for MP1, PIP, DIP and MP2 joint. Objective joint angle of Mp1, PIP, DIP and MP2 joints are 20deg, 60deg, 40deg, -20deg, respectively. The step response is shown in Fig. 7. The response of DIP joint angle had overshoot because of interference from another joints. However, the angles of each joint are converged in about 190ms. Therefore, sufficient high-speed response is realized.

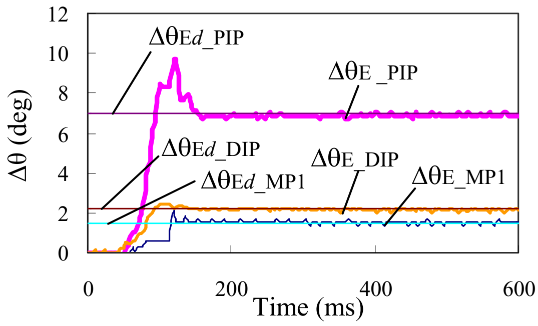


Fig. 9 Response of $\Delta\theta_E$ in force control experiment

B. *Frequency Response*

Second, using index finger of robot finger, the sinusoidal-shaped desired angle,

$$\theta = A_0 \sin(2\pi f t) + \theta_0$$

is applied for each joint. To change the frequency f from 1Hz to 10Hz with 1Hz interval, we obtain the frequency response.

To realize a stretching motion and a lateral fold motion, θ_0 is set as follows:

MP1: 20deg, PIP: 30deg, DIP: 30deg, MP2: 15deg

A0 is set as follows:

MP1: 20deg, PIP: 30deg, DIP: 30deg, MP2: -5deg

The result of frequency response is shown in Fig. 8. The bandwidth of the MP1 joint that has largest inertia was about 5.4Hz. Bandwidth of other joints was more than 10Hz. This controller was stable for 10Hz input. Therefore, this robot hand can realize high-frequency response that exceeds human motion, because maximum tapping ability of humans finger is usually about 5.5Hz due to our experiment.

C. *Force Control Experiment*

Controlling deformation of the elastic elements by positioning ultrasonic motor enables our robot hand to control force. There is a nonlinear relationship between load and deformation of elastic elements because the developed device utilizes nylon yarn for elastic elements. Therefore, we carried out experiments of applying external force to a fingertip to derive the relationship between $\Delta\theta_E$ and joint torque τ in equation (2) at section II *B*. Force control experiments were carried out based on the result.

In the experiment, the target value for fingertip force, F_{yd}, was set to be a vector which component had vertical direction against palm surface. Therefore, ultrasonic motor 4 did not drive. Target values t_d for each joint torque was derived from the Jacobi matrix using F_{yd}, then converted to $\Delta\theta_E$ utilizing relationship as mentioned above. Fig. 9 shows a track record of $\Delta\theta_E$ during force control where F_{yd} was set to be 1.47N. Fig. 9 indicates that each value of $\Delta\theta_E$ was converged to target value around 160ms, and the deformation of elastic elements was controllable by

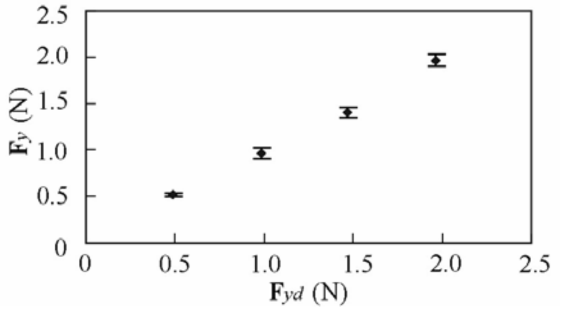


Fig. 10 Result of force control experiment

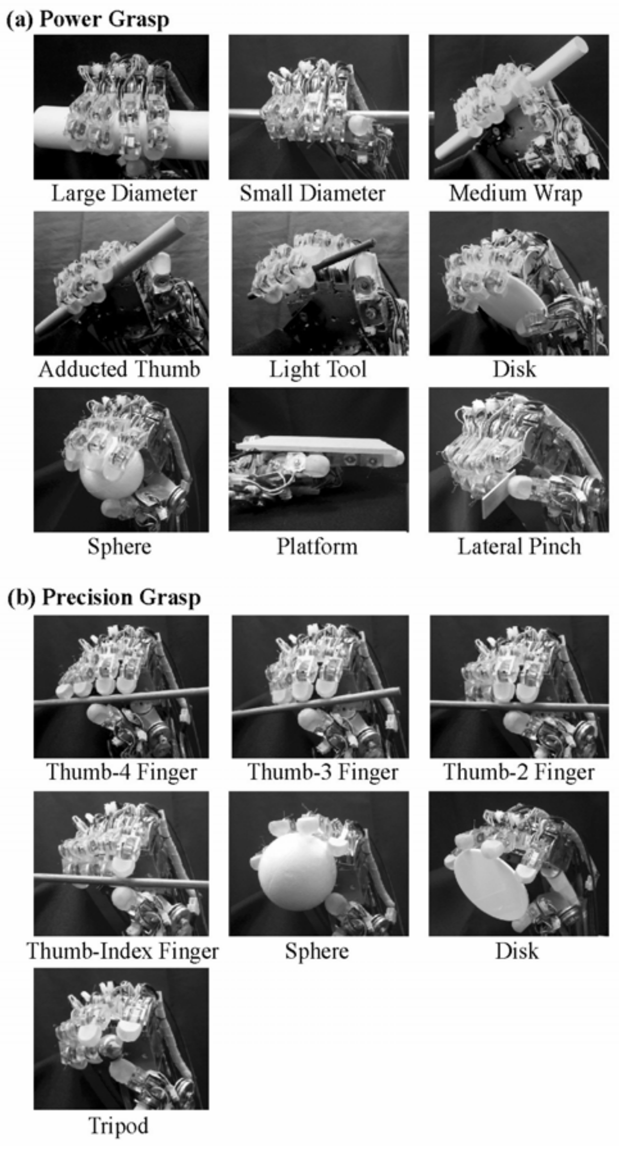


Fig. 11 Result of grasping experiment based on Cutkosky's taxonomy [12]

positioning ultrasonic motors. The value of force output was 1.42N that was close to the desired value.

Next, we carried out five force control experiments for each target value which was varied as follows: 0.49N, 0.98N, 1.47N, 1.96N. As shown in Fig. 10, despite output

Table 1 Comparison of specification of robot hands

Name	Fingers	DOF	Weight[g]	Driving mechanism
Developed robot hand	5	20	853	Built-in actuator
WENDY hand[1]	4	13	1700	Built-in actuator
COG hand[2]	4	12	-	Built-in actuator
DLR hand II[3]	4	13	1800	Built-in actuator
Gifu hand[8]	5	16	1400	Built-in actuator
Utah/MIT hand[5]	4	16	-	Wire-driven
Shadow hand[6]	5	21	-	Wire-driven
Stanford-JPL hand[7]	3	9	-	Wire-driven
Anthrobot hand[9]	5	16	4500	Wire-driven
Robonaut hand[10]	5	12	-	Flex shaft

value had a margin of error because of joint axes friction or hysteresis, the margin of errors are under 10% for each target value. Therefore, it was confirmed that a novel driving method utilizing ultrasonic motors and elastic elements was applied for force control.

D. Grasping Experiment

Next, we carried out grasping experiments to verify that the developed device satisfies the functions of robot hands. Our robot hand can be considered able to do grasping motion just like humans because it has the mechanism like a human hand. To categorize human grasping, power grasp and precision grasp are known for two main classification methods. Cutkosky constructed the novel classification method that has the hierarchical structure based on grasping motion of factory workers [12]. This method is applied to the grasping experiment: our robot hand tried sixteen grasping postures. Fig. 11 shows the results of experiment. Fig. 11 indicates that our robot hand reproduced human grasping posture faithfully. Therefore, it was confirmed that our robot hand has high versatility.

V. DISCUSSIONS

Table 1 shows the comparison of specification of the developed robot hand and previously developed robot hands [1]-[10].

Our robot hand has 20 DOF. It is the largest DOF among the built-in actuator type robot hands. We can conclude that our hand is the only built-in actuator type robot hand having almost the same DOF and size as human hands.

Mass of our hand is only 853g. It is lightest among the compared robot hands. It is advantageous in connectivity to various robot arms.

The elastic element of our robot hand is also advantageous in passive compliance as well as stable grasp force due to strain energy of the elastic element even when the power of the motor is off.

Our hand realized the motion of fingers faster than human's by use of semi-direct drive by ultrasonic motors. Grasping force is also large compared with other built-in actuator type robot hands because ultrasonic motors can generate larger torque compared with other direct drive motors.

Due to the above mentioned characteristics, our robot hand is effective for use as an end effecter of robots carrying out skillful grasping and manipulation substituting for humans. It can be applied to humanoid robots and master-slave robot systems. Especially, it can substitute human skills including surgery and arts when it is used as tele operation systems.

Construction of five-fingered master-slave robot system is one of the possible future works. Control of the robot hand as an autonomous robot hand is also needed to be studied.

VI. Conclusions

In this paper, design, implementation and control experiments of a five-fingered robot hand that has measurement, shape and DOF equivalent to human hands is mentioned. Our robot hand has advantages over other robot hands in terms of DOF and weight, thus it can be said that our robot hand is highly sophisticated as an end effecter for human operation. For future works, improvement of reliability, mounting to a robot arm and implementation of tactile sensors are considered. In addition, we will apply this hand for a variety of uses including tele-operation in a master-slave system.

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