The 2009 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 11-15, 2009 St. Louis, USA

NAIST Hand 2: Human-sized Anthropomorphic Robot Hand with Detachable Mechanism at the Wrist

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Abstract— **Humanoid robots and robotic manipulators with good dexterity are promising to enhance the factory productivity in next generation. Dexterity of robotic manipulators can be achieved by equipping an anthropomorphic robot hand with multiple fingers. Additionally, in order to manipulate various tools that humans are using in daily life, the size and the exerting force of the robot hand should be similar to that humans are. In this paper, we proposed a human-sized multi-fingered robot hand with detachable mechanism at the wrist. The robot hand can be split at the wrist into the hand part and the actuator part. The fingers are driven by wires and are controlled by actuators embedded in the arm part. The driving force from the arm part is transmitted to the hand part by gear mechanism at the wrist. The developed robot hand has the size of 200[mm](length) $\times$ 78[mm](width) $\times$ 24.6[mm](thickness) and can exert 10[N] at the fingertip. The performance of the developed robot hand was shown by a motion control experiment.**

I. INTRODUCTION

A multi-fingered dexterous robot hand is promising tools for factory automation, nursing and caring system, and robots living with humans. There are many works developing anthropomorphic robot hands. These robot hands can be divided into following categories from the viewpoint where the actuators are embedded;

1) The actuators are embedded inside the palm and/or the fingers.
2) The actuators are embedded outside the hand part, for example in the forearm.

In case of embedding the actuators inside the palm/fingers, the finger joints are directly driven or via gears by the embedded actuators. Gifu Hand II [1], Gifu Hand III [2], DLR Hand [3], and NAIST Hand [4] are good samples that have actuators inside the palm/fingers. By integrating the actuators into the hand part, whole robot hand unit becomes compact. However, it is not easy for such type of robot hands to achieve small size and large fingertip force together. When a small actuator is selected in order to mimic the human hand size, the available force becomes small e.g., the size of Gifu Hand III is similar to that of human, but the fingertip force is about 3[N]. On the other hand, DLR Hand can reach a large fingertip force (10 $\sim$ 30[N]), but the size is larger than that of human hand.

In case of embedding the actuators outside the hand part, the driving force has to be transmitted from the actuators to the finger joints. Utah/MIT HAND [5], Robonaut Hand [6], UB Hand 3 [7] and Shadow Hand [8] have adopted tendon driven mechanism to control the fingers. By using this mechanism, a small and light hand part can be designed. Because we can choose any actuators without affecting the size of the hand part, a human-sized robot hand with a high fingertip force can be developed. However, the maintenance becomes more complicated because the forearm part that loads the actuators is necessary in addition to the hand part.

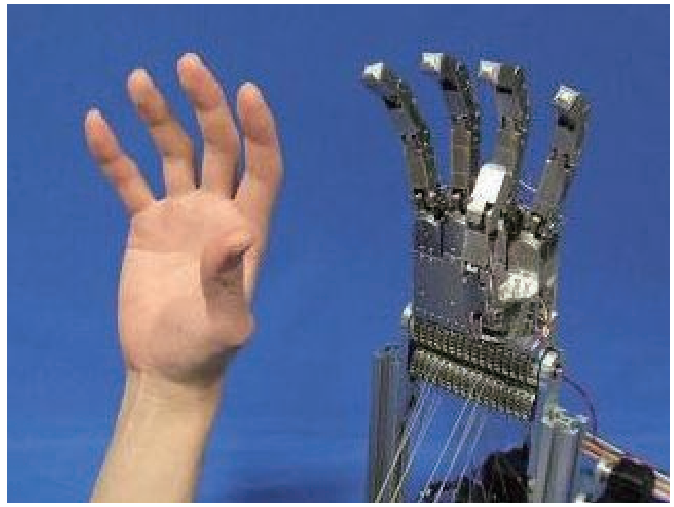

Fig. 1. Anthropomorphic robot hand: NAIST Hand 2

In this paper, we propose a human-sized anthropomorphic robot hand 'NAIST Hand 2' (Fig. 1) that achieves both small size and large fingertip force enough to manipulate tools that human uses in daily life. In order to design a small hand with a large fingertip force, we adopted tendon driven mechanism to drive the fingers. Furthermore, the NAIST Hand 2 has detachable mechanism at the wrist and it can be split into the hand part and the actuator part. The driving forces from the actuators are transmitted to the fingers through gear mechanism at the wrist. The gear mechanism at the wrist makes the hand part and the actuator part splittable. By splitting the hand part and the actuator part, we can separately maintain each part. Moreover, we can easily replace the actuator part depending on the task, such as servomotors and air muscles.

The developed robot hand has the size of 200[mm](length) $\times$ 78[mm](width) $\times$ 24.6[mm](thickness) and can exert 10[N] at the fingertip. The performance test shows the effectiveness of the developed mechanism.

This work was supported by KAKENHI (20700161).

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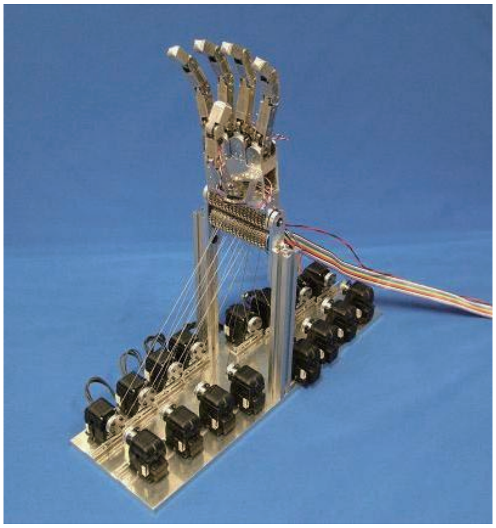
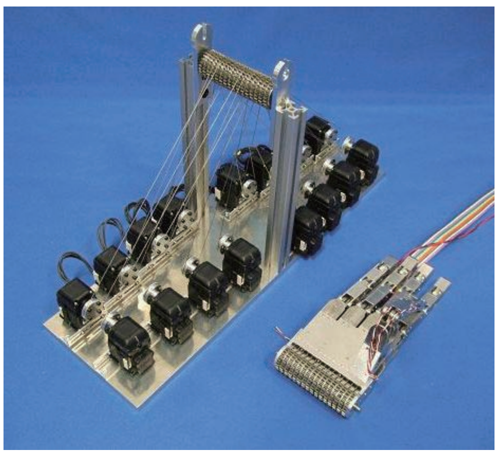


(a) Overview



(b) Hand part and actuator part

Fig. 2. Developed robot hand system

II. MECHANICAL DESIGN

A. Concept

The 'NAIST Hand Project' has been started at Nara Institute of Science and Technology in 2002. Especially, in regarded to the tactile sensation and manipulation, we have proposed a vision-based slip margin estimation and grip force control by its direct feedback [9]. The NAIST Hand was developed as a platform for these researches [4]. The hand has four fingers and each finger has three degree of freedom. Its specially designed gear mechanism has relaxed the restriction on the space for actuators, and all actuators are embedded in the palm. Nevertheless, the size of the NAIST Hand (370[mm] for the finger and the palm) is larger than that of human, and the fingertip force (5[N]) is not enough to manipulate tools that human uses.

In this paper, we propose a human-sized anthropomorphic robot hand with a high fingertip force. The characteristics of the 'NAIST Hand 2' are as follows:

1) Human-sized fingers and hand
2) The hand part and the actuator part can be split at the wrist
3) The gear shaft for driving the finger joints is shared with the wrist joint axis.

1) Human-sized fingers and hand: To develop the human-sized robot hand, the actuators are located outside the hand and the finger joints are coupled with the actuators by wires. By embedding the actuators outside the hand part, we can select any actuators without concern for the size of the actuator. Additionally, we have developed a small and thin pulley for driving the joints. The pulley is used to design the robot hand comparable to human.

2) Detachable wrist: The fingers of the tendon driven robot hand are driven by the actuators located in the forearm via wires running from the actuators to the finger joints. Consequently, the whole hand system becomes large and the maintenance work becomes hard. To solve the problem, we have designed detachable mechanism at the wrist. The driving forces from the actuators are transmitted to the fingers through gear mechanism at the wrist. The gear mechanism at the wrist makes the hand part and the actuator part splittable. By splitting the hand part and the actuator part, we can separately maintain each part. Furthermore, we can easily replace the actuator part depending on the task, such as servomotors and air muscles.

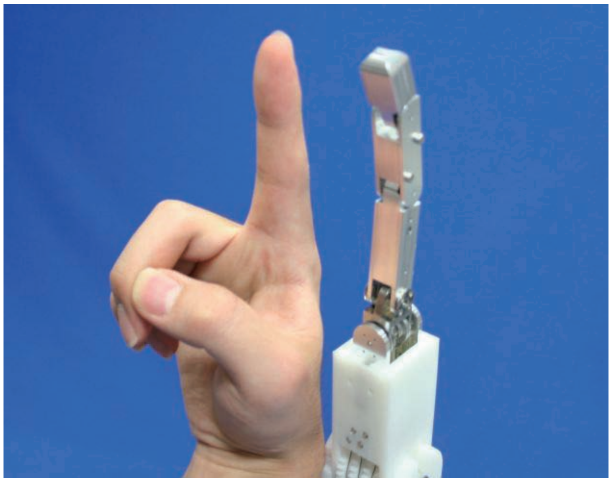
3) Sharing wrist axis: The gear mechanism at the wrist is arranged in line and a shaft supports the gears. The finger motions are influenced by the wrist motion because all the wires are connected to the wrist axis. By sharing the gear shaft for driving fingers with the wrist joint axis, we can analytically correct the finger motions when the wrist joint moves.

B. Mechanical profile

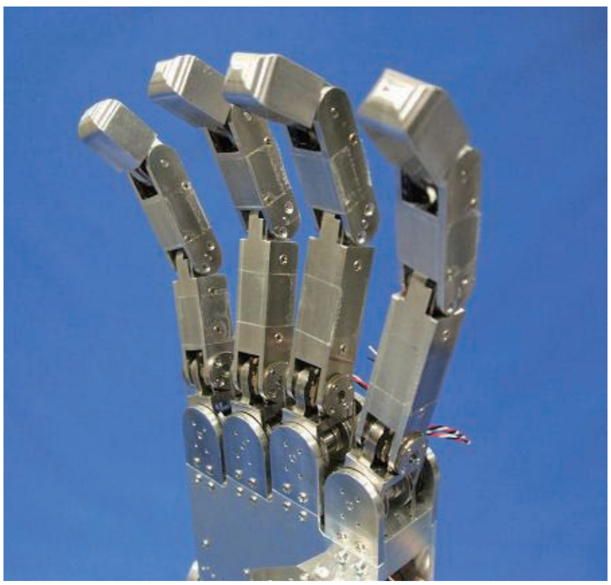
Fig. 3 shows the fingers of the developed robot hand; NAIST Hand 2. The size of the finger and the palm are designed to be approximately same to that of human. Fig. 4 and Table I show the dimensions of the NAIST Hand 2. The dimensions were determined by reference to Japanese Body Dimensions Data provided by AIST [10]. The palm width (78.0[mm]) and thickness (24.6[mm]) is less than the average of Japanese adult male. Considering the wiring space inside the palm, we designed the hand length a little larger than human (200.0[mm]). The finger width (12.4[mm]) and thickness (11.0[mm]) were designed to be less than human because skins will be equipped on the fingers. The finger length (100[mm]) is approximately same to that of human. The length of the thumb and the little finger (90[mm]) are 10[mm] less than other fingers by cutting the 3rd link 10[mm].

The number of joints is 21 (four joints for each finger and one joint for wrist) and the degree of freedom (DOF) is 16 (three for each finger and one for wrist). In the current configuration, the fingertip force is 10[N] due to the specification of the actuators used.

Table II shows the weight of the robot hand. The weight of each finger is 85[g], and the weight of the hand part

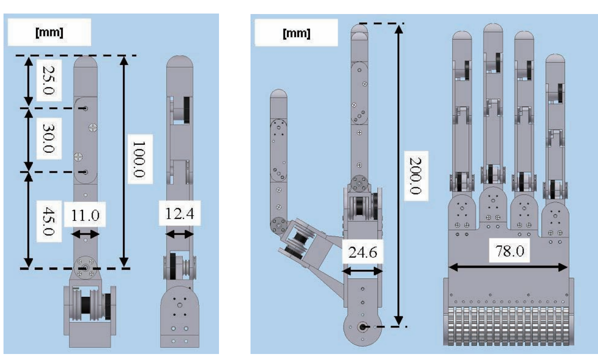


(a) Size of the finger



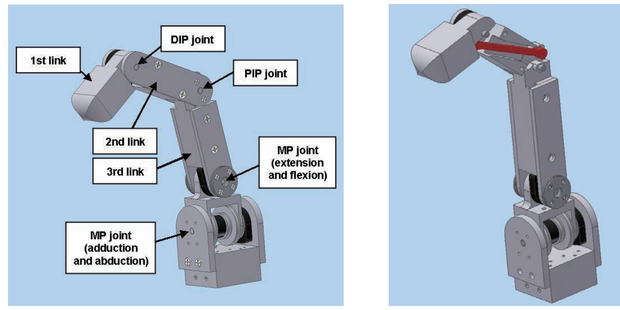
(b) Fingers

Fig. 3. Developed fingers



(a) Finger (b) Hand

Fig. 4. Dimension of the finger and the hand



(a) Solid model of the finger (b) Joint coupling

Fig. 5. Design of the finger module

(including five fingers and palm) is 665[g]. In the current configuration, the actuator part consists of 16 servomotors and the base for fixing the actuators. The weight of the current actuator part is heavy (3300[g]) because we designed a simple wire-driven mechanism for the actuator part. The weight will be reduced by further sophistication in the design of the actuator part.

C. Finger Module

Each finger module has three joints (MP, PIP, and DIP) as shown in Fig. 5(a). The MP joint has two DOF for the adduction/abduction and the flexion/extension motions. The PIP joint has one DOF for the flexion/extension motion. The DIP joint's flexion/extension motion is coupled with the PIP motion by a linkage. This is based on the knowledge in physiology that human's PIP and DIP joint synchronize. As a result, each finger has three DOF. Fig. 5(b) shows the coupling mechanism of the flexion/extension mechanism of PIP and DIP joints. The motion of the DIP joint is linear to that of the PIP joint. Each joint is built with stainless and the linkage is built with carbon steel to enhance the strength.

Fig. 6(a) shows the kinematics of each joint. The working

TABLE I

DIMENSIONS AND PROFILE

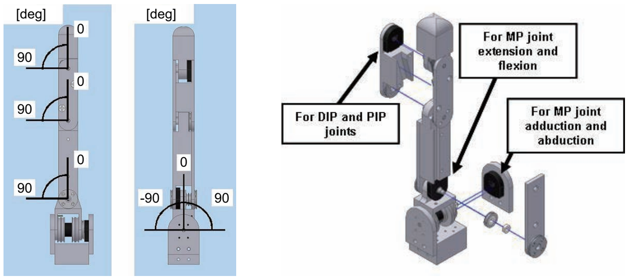
	NAIST Hand 2	Adult male
Palm width [mm]	78.0	84.0
Palm thickness [mm]	24.6	27.5
Hand length [mm]	200.0	190.0
Finger width [mm]	12.4	17.3
Finger thickness [mm]	11.0	16.5
Finger length [mm]	100.0 (90.0†)	99.0 (index)
1st link length [mm]	20.0	
2nd link length [mm]	30.0	
3rd link length [mm]	45.0 (35.0†)	
Number of joints	21	24 and more
Fingertip force [N]	10 and more	20 and more

†Thumb and little finger

TABLE II

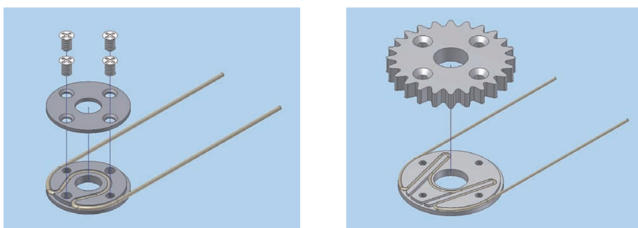
WEIGHT

Finger	85[g]
Hand part	665[g]
Actuator part	3300[g]
Whole hand system	3965[g]



(a) Kinematic design (b) Assembly

Fig. 6. Model of the finger



(a) For fingers (b) For wrist

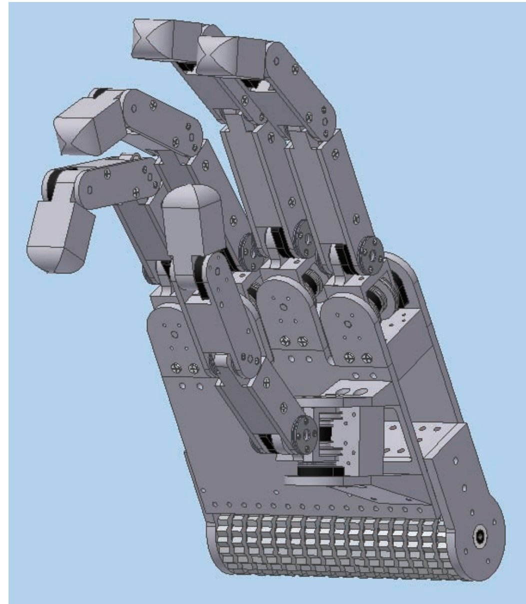
Fig. 7. Pressure bonding pulley

range of the DIP and PIP joints are $0 \leq \theta_{PIP}, \theta_{DIP} \leq 90$[deg], and the range of the MP joint is $-90 \leq \theta_{MP} \leq 90$[deg]. However, the actual working range of the MP joint is approximately $-30 \leq \theta_{MP} \leq 30$[deg] because of the collision with the neighboring fingers. Each finger has three rotary potentiometers to measure the joint angles as shown in Fig. 6(b).

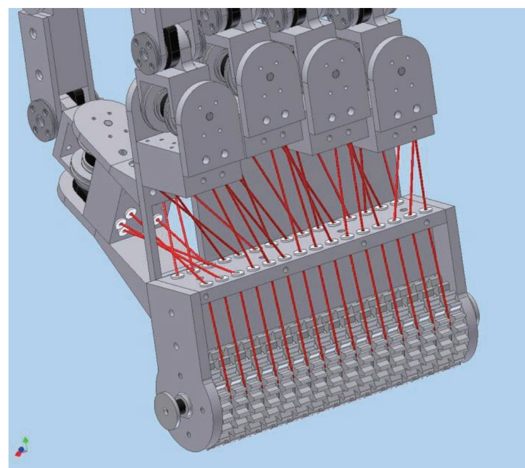
In order to make a human-sized finger, we designed a thin and small pulley for driving the joint. The pulley designed is shown in Fig. 7. The pulley consists of the cover part and the base with wire guiding groove. The wire is set along the guiding groove and held by screwing the cover part. By using this mechanism, we can develop a thin (1.6[mm]) pulley. The developed pulley is used in each joint and it contributes to design a human-sized finger.

D. Wrist and Arm

Fig. 8(a) shows the overview of the hand part and Fig. 8(b) shows the wiring inside the hand part. The wire to drive the finger joint runs from the joint pulley to the corresponding gear. 15 gears for the finger joints and one gear for the wrist joint are arranged at the wrist of the hand part. The actuator part also has 16 gears. The driving forces from the actuators are transmitted to the fingers through the gears at the wrist. Fig. 9 shows the design of the wrist and Fig. 10(a) is the picture of the force transmission mechanism at the wrist. The gear mechanism is arranged in line and the shaft supports the gears. By sharing the gear shaft with the wrist joint axis, analytical correction of the finger motions when the wrist joint moves is achieved. Additionally, the gear mechanism at the wrist makes the hand part and the actuator part splittable. Fig. 10(b) is the picture when the hand part and the actuator part is split.



(a) Hand part



(b) Inside the palm

Fig. 8. Solid model of the hand

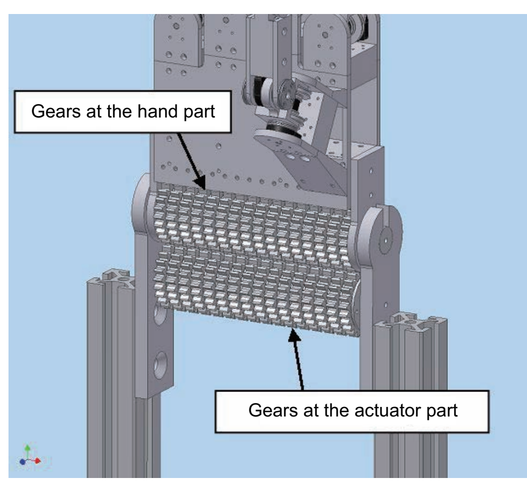
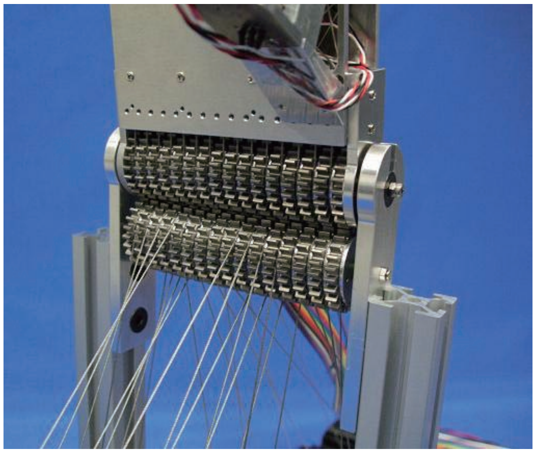
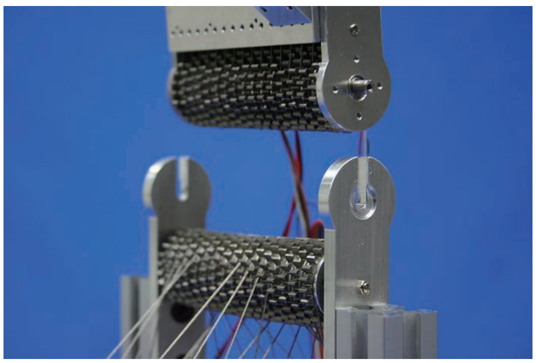


Fig. 9. Design of the wrist



(a) Force transmission mechanism



(b) When splitting at the wrist

Fig. 10. Detachable mechanism at the wrist

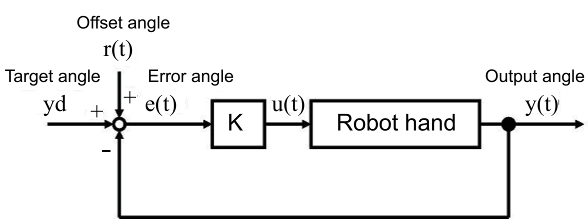


Fig. 11. Control block diagram of the joint angles

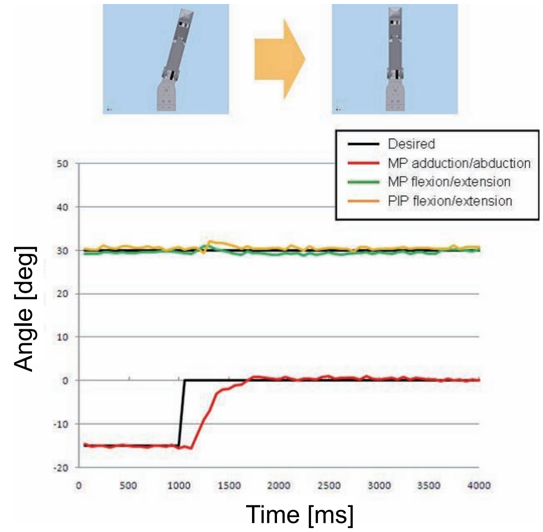


Fig. 12. Results of the finger joint angle control

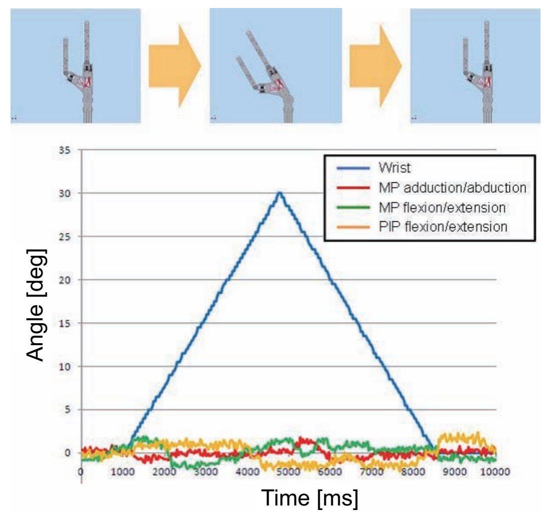


Fig. 13. Results of the wrist control

III. CONTROL AND PERFORMANCE

A. Control of Joint Angles

When a particular finger joint moves, other joints move together because the wire runs via some pulleys corresponding with other joints. Therefore, the motion correction of the joints coupled with the moving joint is necessary. Additionally, the backlash of the gears causes the error in the joint control. In this paper, P–control is used to correct the errors. The block diagram of the joint angle control is shown in Fig. 11.

The PIP and MP joint motions are shown in Fig. 12. In the figure, the initial position is set as 30[deg] for the PIP and the MP flexion/extension, and -20[deg] for the MP adduction/abduction, and then the MP adduction/abduction joint moves from -20[deg] to 0[deg]. The angle of the MP adduction/abduction joint achieves the desired angle, and the other joints are not influenced by the MP adduction motion.

The finger joint motions are influenced by the wrist motion without the motion correction because all the wires are connected to the wrist axis. Therefore, in order to control the wrist and the fingers independently, the motion correction of the finger joints according to the wrist motion has to be implemented. In our mechanism, the analytical correction of the finger motions can be easily achieved because the gear shaft for driving the finger joints and the wrist joint axis is same. Fig. 13 shows the finger joint angles when the wrist joint moves 0[deg] to 30[deg]. We can observe that the finger joints are not significantly influenced by the wrist motion. This result indicates the effectiveness of the developed mechanism and the motion correction.

Generally, the wire-driven mechanism presents non-linear behaviors due to the elasticity of the wire. Some researchers have focused the control problem of the wire-driven hand [11], [12], [7] and we need to consider the control ploblem

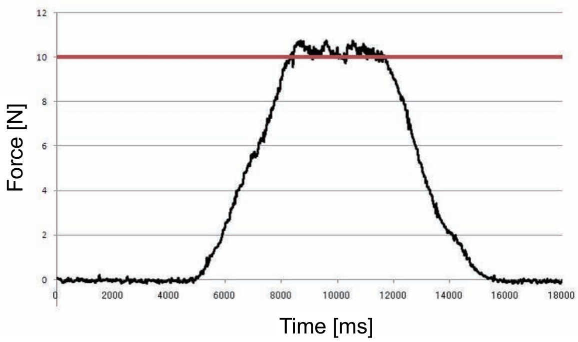


Fig. 14. Fingertip force

Fig. 15. Bottle grasping

for precise maniplulation tasks.

B. Fingertip Force

The maximum fingertip force was measured and the result is shown in Fig. 14. In the current configuration, the NAIST Hand achieved the force of 10[N] (approximately 10.5[N]). Although the force is less than that human can exert, it is large enough to manipulate and grasp most tools that human uses in daily life. For example, the NAIST Hand 2 can firmly grasp a plastic bottle of 500[g] as shown in Fig. 15. The fingertip force is able to be increased by replacing the current actuator part with much more powerful one.

IV. CONCLUSION

In this paper, human-sized anthropomorphic robot hand: NAIST Hand 2 was developed. The NAIST Hand 2 has some unique mechanisms:

1) Human-sized fingers and hand
2) The hand part and the actuator part can be split at the wrist.
3) The gear shaft for driving the finger joints is shared with the wrist joint axis.

In order to design a small hand part with a large fingertip force, we adopted tendon driven mechanism to drive the fingers. Furthermore, the NAIST Hand 2 has detachable mechanism at the wrist and it can be split into the hand part and the actuator part. The driving forces from the actuators are transmitted to the fingers through gear mechanism at the wrist. The gear mechanism at the wrist makes the hand part and the actuator part splittable. By splitting the hand part and the actuator part, we can separately maintain each part. Moreover, we can easily replace the actuator part depending on the task. The gears at the wrist are arranged in line and a shaft supports the gears. By sharing the gear shaft for driving fingers with the wrist joint axis, we can analytically correct the finger motions when the wrist joint moves.

In order to design a human-sized finger, we developed a thin and small pulley for driving the joint. The pulley consists of the cover part and the base with wire guiding groove. The wire is set along the guiding groove and held by screwing the cover part. The developed pulley is used in each joint and it contributes to design a human-sized finger. The developed robot hand has the size of 200[mm](length) $\times$ 78[mm](width) $\times$ 24.6[mm](thickness) and can exert 10[N] at the fingertip. The performance test showed the effectiveness of the developed mechanism and the motion correction.

Future work includes equipping tactile sensors and soft skins on the fingers. Since the NAIST Hand 2 can easily replace the arm part, we plan to develop a human-like forearm with variety of actuators, such as rubber artificial muscles.

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