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Development of a Miniature Robot Finger with a Variable Stiffness Mechanism using Shape Memory Alloy

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Abstract

This paper describes a miniature robot finger which uses shape memory alloy as the actuator. Aiming at developing robot hands to perform human work instead of men, numerous research have been conducted. By miniaturizing robot hands, execution of more detailed work becomes possible. In developing miniature robot hands for dexterous manipulation, it is necessary to consider miniaturizing and simplification. The miniature robot finger proposed in this paper is driven by shape memory alloy (SMA) wires. The structure of the robot finger imitates the musculo-skeletal system of humans, since SMA wires exhibit nonlinear features similar to human muscles. Highly precise position control of fingertip is performable by using SMA owing to its shape memory effect. Force control of the fingertip is performed by measuring the tension of the SMA wire. We used strain gages to measure tension. We confirmed that stiffness control of the finger joint can be conducted by controlling tension of the SMA simultaneously.

1. Introduction

Research and development robots to take the place doing human work are prosperous. Human hands are important as an end-effecter to the external environment when interacting with an object. Likewise, as an end effecter, robot hands are important for robots in performing operations.

Robot hands can be divided into three categories: mechanical grippers, special purpose hands, and universal hands [1]. The former two types are for limited use, so the form is generally not manlike, and are often used for industrial robots. On the other hand, the humanoid robots belong to the last type because steady and smooth grasping and handling of various types of objects is required. Universal hands can also be used for other purposes such as tele-operation in outer space, in hazardous environments and in tele-surgical situations. Therefore, the development of universal robot hands have been an interesting topic among researchers, and a lot of sophisticated robot hands have indeed been developed all over the world [2]-[6].

There are two types of driving mechanisms for existing robot hands: (1) built-in actuator type and (2) external actuator type. The former type of robot hand generates motion of fingers by using motors installed inside the finger or the palm. The dexterous hand for WENDY [2] and DLR II [3] are classified as in this type. On the other hand, the latter helps make the finger structure simple and light by using wire or belt driven mechanisms. The Utah/M.I.T hand [4], Robonaut hand [5], and shadow hand [6] are classified as this type.

Evident from above, a robot hand has many degrees of freedom (DOF), which makes complicated motion like that of a human finger human finger possible. If the end-effecter is to take the place of humans in doing work, operating is easier by copying the form of the human hand. It is desirable for an operator becomes possible for an operator to make a robot hand reproduce the same motion as operator’s finger. It is desirable for an operator to make operation of a finger expand and reduce owing to the scale effect. The operator can than do detailed work by using a miniature robot finger. However, in past research, miniaturization of robot fingers is difficult because the driving mechanism is complicated.

There is research that focus on human musculoskeletal systems [7]. The human finger possesses a structure called the extensor mechanism, a web-like collection of tensions material that lies on the dorsal side of each finger and connects the controlling muscles to the bones of the finger. By imitating this,

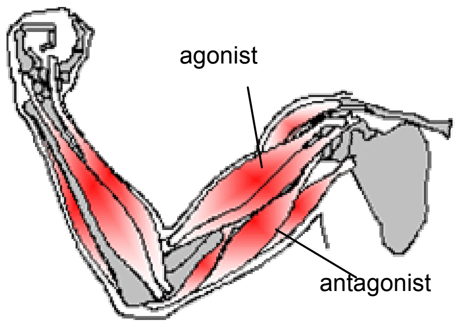


Figure 1. Human musculoskeletal

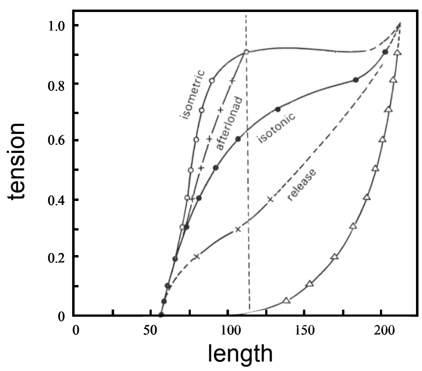


Figure 2. Length and tension of muscle

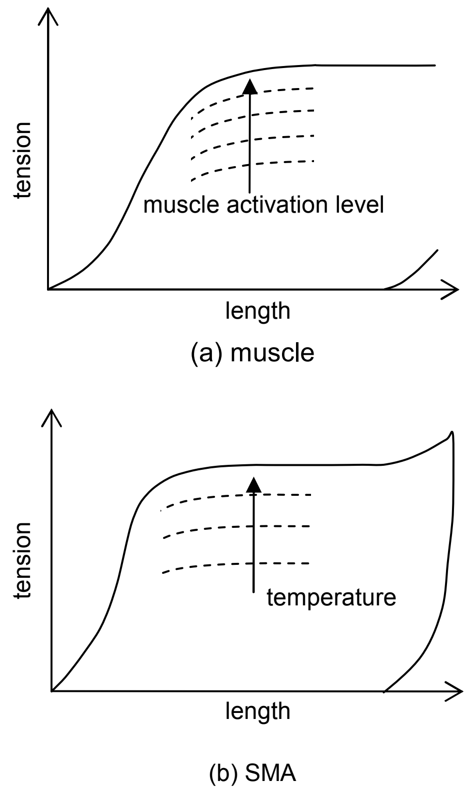


Figure 3. Length and tension of muscle

the finger motion can be reproduced. Attempts for miniaturization are prosperous. Micro grippers that can execute micro operations have been developed [8]. However, multi DOF miniature robot hands are necessary in order to manipulate miniscule objects with dexterity. Driving mechanisms aiming at miniaturization have been proposed [9], [10]. Ogahara ' s joints, with the fingers wire-driven by actuators placed outside the robot hand [9]. Moreover Lotti proposed a simple driving mechanism which uses two wires [10]. However, these driving mechanisms cannot perform high precision position control because of the use of wires.

In this research, we propose a driving mechanism of the joint of a robot finger that can be miniaturized and is highly versatile. The mechanism imitates the human musculo-skeletal system.

The mechanism uses shape memory alloy (SMA) wires as an actuator. Owing to the shape memory effect that SMA exhibits, a small-sized robot finger with large output can be developed. The robot finger can perform position control, force control, and stiffness control. The problem of the response of SMA can be improved by using SMA wires with a small diameter.

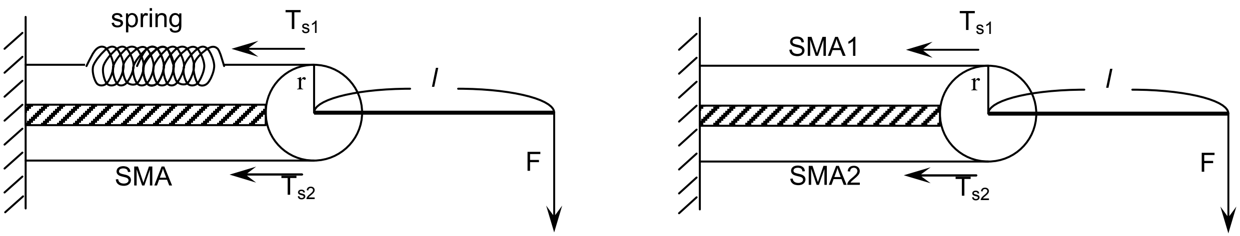
The conceptual design of this robot finger, the driving method which imitates the human musculo-skeletal system, the basic design of robot finger, the drive mechanism of robot finger using two SMA wires, and detail design are described in chapter two. Next, implementation and evaluation is described in chapter three. Finally, conclusions and future works are presented in chapter four.

2. Design

2.1 Concept Design

The desired robot finger is small and can perform position control, force control, and stiffness control. Output of conventional DC motors is proportional to the volume of the motor. Therefore, a power/weight ratio becomes small by miniaturizing DC motors. In contrast, the output of SMA is proportional to area. Therefore, the power/weight ratio becomes large by miniaturizing the SMA wire. This is why SMA was implemented as the actuator for this robot finger.

We focused on the human musculo-skeletal system in conducting position control, force control, and



(a) spring – SMA type (b) SMA – SMA type

Figure 4. Driving mechanism

Table 1. Feature of SMA

Diameter of wire [mm]	0.05	0.075	0.1	0.15	0.2
Contraction [%]	5	5.4	5	4.2	3
Average contraction velocity [mm/s]	5.6	6.8	6.2	4.7	2.5
Average extension velocity [mm/s]	3.9	1.6	1.2	0.3	0.1
Generative force[N]	0.9	1.9	2.7	3.2	6.7

stiffness control. Figure 1 shows the view showing a frame format of human musculoskeletal system. The human musculo-skeletal system consists of agonist and antagonist muscles. The joint of a human limb is driven by contraction and extension movements of muscles. Figure 2 shows the relationship between the muscle length and tension. The muscles exhibit nonlinear relationships between length and tension. It enables muscles to perform position control, force control, and stiffness control with these characteristics.

Next, the feature of SMA is described. SMA is a metal that, after deformed, returns to its original form when heat is applied. SMA generates form recovery strain, when heated. Thus, the length of SMA expands and contracts. The major advantages of SMA are the high power weight/ratio of SMA when miniaturizing and the easiness of disposition when used as an actuator. The former is due to the fact that the output of the conventional electromagnetism motor is proportional to volume, while the output of SMA is proportional to area. The latter owes to the fact that SMA is flexible in a low temperature condition. On the other hand, the main disadvantage of SMA is that temperature control is difficult and the response is slow. Temperature control is considered difficult due to the nonlinear stress / strain relationship and form recovery strain / temperature relationship. However, in the proposed driving mechanism the length of SMA wires

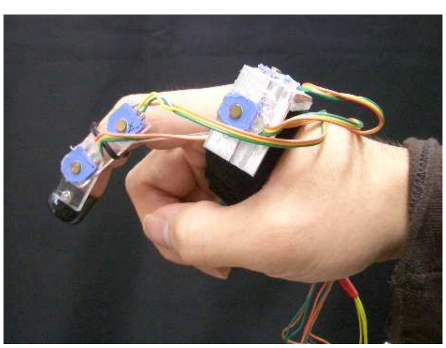


Figure 5. The measuring device

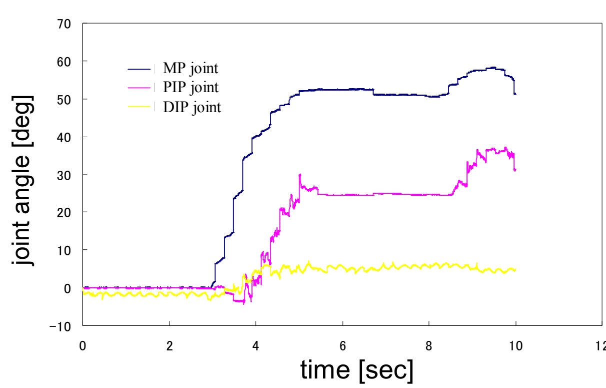


Figure 6. The maximum joint angle

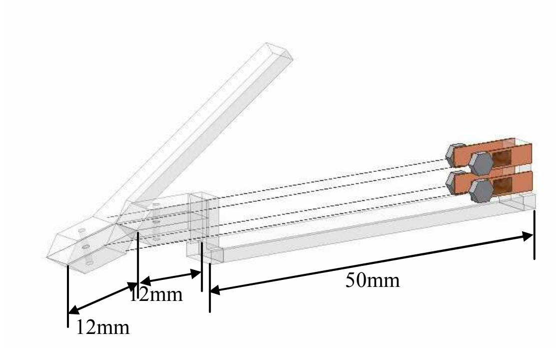


Figure 7. The size and form of robot finger

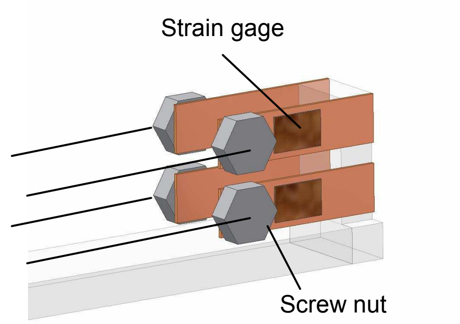


Figure 8. The force sensor

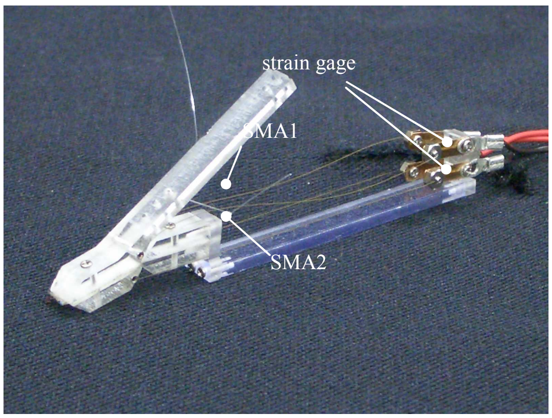


Figure 9. The manufactured miniature robot finger

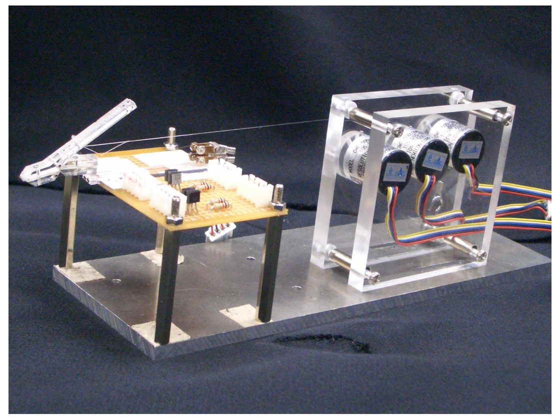


Figure 10. The experiment device

is controlled to overcome the weakness. The latter is because displacement of the length of SMA by shape memory effect is determined by the temperature. To compensate for this disadvantage, we implemented an extremely thin SMA wire. If the diameter of SMA wire is small, response will improve.

Figure 3 shows the relationship between length and generative force of muscles and SMA, and illustrates how they are qualitatively similar. Muscles exhibit a nonlinear relationship between tension and length. The relationship is controlled by changing a control parameter known as the muscle activation level. SMA has nonlinear relationships between a stress and a strain. Moreover, the relationship is changed by control parameter as temperature. As mentioned above, SMA is similar to muscles in the relationship between length and generative force, and that there is a control parameter by which the nonlinear relationship can be changed.

n this paper, we propose a driving method which expands and contracts by heating and cooling SMA.

2. 2. Basic Design

In this section, we describe the driving mechanism of the miniature robot finger. There are two types of driving mechanisms using SMA. The one shown in Figure 4. (a) is composed of SMA and a spring. We can adjust the angle of joint rotation arbitrarily for the finger to carry out bending movement. However, the spring force will determine passively when a finger carries out extension movement. On the other hand, two SMA wires constitute the second type (b), and is called the antagonist SMA model. We can adjust the angle of joint arbitrarily when a finger carries out extension and bending movements. Therefore, we adopt this driving mechanism as shown Figure 4 (b).

2. 3. Detail Design

In this section, the detailed design of the miniature robot finger is explained: the selection of SMA as an actuator, the determination of a range of motion of joint, the selection of size and form of miniature robot finger, and the choice of the angle measurement device and force sensor. First, we measured the speed of expansion and contraction and generated force to evaluate SMA wires as an actuator. From the results shown in Table 1, the actuator to be used was determined as SMA wires of 75 μm in diameter. Secondly, we measured the motion range of human finger joints in conducting precision grasping of an object using the device shown Figure 5. Figure 6 shows the results. The maximum joint angle was 58deg. Therefore, the motion range of the joint of the miniature robot finger was determined to be 0-60deg. Third, the size and form of a miniature robot finger was determined considering the deployment of SMA wires and the adopted motion range of the finger. Figure 7 shows the size and form of miniature robot finger. The size of the manufactured robot finger is 1/4 of a human finger. The SMA wires were arranged as shown in Figure 7. Moreover, nonwoven fabric was used for the joint hinge part. Nonwoven fabric exhibits excellent folding and twisting endurance. Finally the measurement devices were selected. Encoders are used for measuring the joint angle. The joint angle is transmitted to an encoder by the wire. Strain gages are used to measure the generated force. Each strain gage is bonded to a small copper plate and is arranged at the end of SMA wire. Figure 8 shows the measurement of generative force equipment. We arrange a copperplate as a cantilever. SMA generates tension, and the copper plate produces strain.

The miniature robot finger and experiment device were manufactured by combining the component mentioned above. Figure 9 shows the manufactured miniature robot finger and Figure 10 shows the experiment device.

3. Implementation and experiment

To evaluate the driving mechanism (see p2 caption), experiments were conducted. We conducted position control, force control and stiffness control experiments using the manufactured miniature robot finger and experimental setup. Also, this system was controlled using a micro computer H8/3048. First, the control system was constructed. Figure 11 shows the schematic view of the control system. The miniature robot finger is connected to the H8/3048. The joint of miniature robot finger is driven by heating and cooling SMA. SMA is heated by applying electricity. Pulse Width Modulation (PWM) was performed, in which the average voltage applied is controlled by changing the duty ratio. The SMA wire is cooled by natural heat dissipation. Each experiment conducted using this control system is described below.

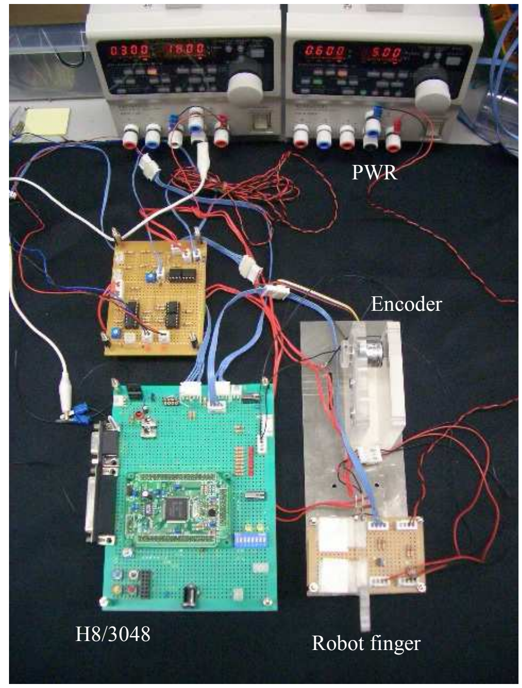


Figure 11. The control system

3. 1. Position Control

In this section, the position control experiment is described: the step response of system and response in a master-slave system.

The step response of system was examined by giving numerical input. The initial angular position of the joint is set at 0 deg. Then a step input of 10 deg and 30 deg were given, respectively. For controlling the length of the SMA wire, a proportional integral feedback controller:

$$V = K_p(\theta_d - \theta) + K_i \int e(t)dt \qquad (1)$$

was used. Where θ_d is angular position of step input, θ is angular position of joint, e(t) is deviation, V is a average voltage applied to the SMA wire, K_p is the proportional feedback gain, and K_i is the integral feedback gain.

Figure 12 shows the results of the step response experiment. When the target angle was 10 deg, the angle of the joint reached the target angle in approximately 100 ms. When the target angle was 30 deg, the time it took was 150 ms. The results were of the same order as human response. By miniaturizing the robot finger more, the position control response should become quicker than humans. As shown above, we were able to perform high precision position control and could obtain the rapid response.

Next, the response in a master-slave system was examined. The developed robot finger served as the slave finger, while we developed a simple 4 linked master finger with 4 DOF which directly measures the four angular positions of the index finger of the operator. The miniature robot finger was controlled to follow the motion of the MP joint of the master finger. Lengths of the SMA wires were controlled by a proportional feedback controller:

$$V = K_p(\theta_d - \theta) \quad (2)$$

where θ_d is angular position of joint of miniature robot finger, θ is master finger, V is a average voltage applied to the SMA wire and K_p is the proportional feedback gain.

Figure 13 shows the result of the experiment in a master-slave system. There is little oscillation, and the angular position of the miniature robot finger successfully followed the angle of the MP joint of the master finger with a time-lag of 150 ms, which can be considered rapid enough for practical use. From these results, we confirmed that SMA wires can be cooled enough by natural heat dissipation when the diameter of the SMA wire is small. If the diameter is smaller more, it is just conceivable that the response will improve further.

3. 2. Force Control

In this section, the force control experiment is described. The tension of SMA was measured by a

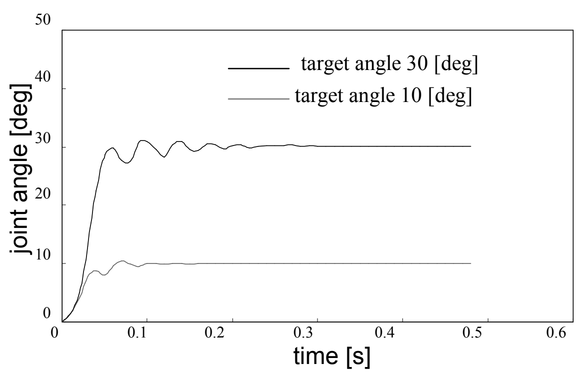


Figure 12. Step response

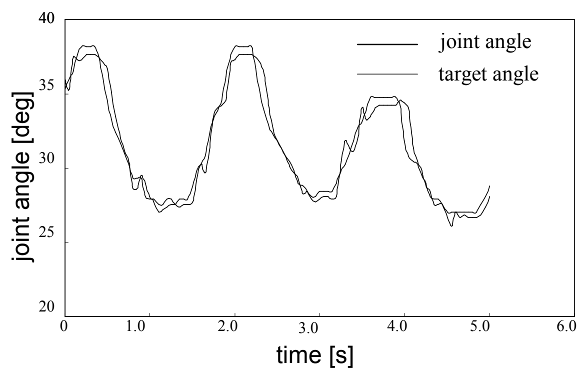


Figure 13. The response of master-slave

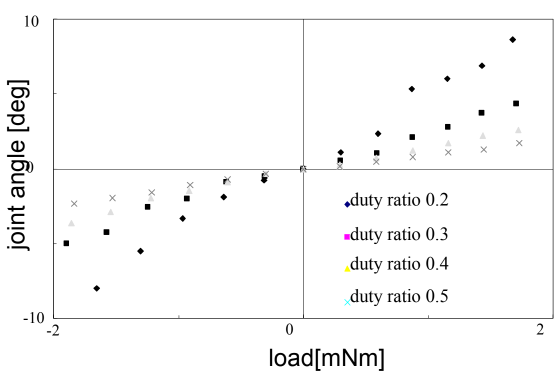


Figure 14. Stiffness control

Table 2. The results of force control

Target force [N]	Value of Strain gage	Generative force[N]
0.098	5	0.114
0.294	10	0.296
0.490	15	0.495

strain gage and generated force was controlled. Force control was examined by giving numerical input. Target force of 0.098, 0.294 and 0.490 N at the fingertip were given to the miniature robot finger. For controlling the tension of SMA, a proportional feedback controller was used:

$$V = K_p (F_d - F) \qquad (3)$$

where F_d is that target force at the fingertip, F is the generated force, V is a average voltage applied to the SMA wire, and K_p is the proportional feedback gain.

Table 2 shows the results of the force control experiment. The error between the target force and measured value was within approx 10 %. Thereby, we confirmed that it was possible for the developed miniature robot finger to control fingertip force by measuring the tension of SMA wires using strain gages.

3. 3. Stiffness Control

In this section, the stiffness control experiment is described. Equal voltage is applied to the two SMA wires arranged on the upper and lower sides of a miniature robot finger, thus generating tension. Therefore tension of the SMA wires can be changed by adjusting the average voltage. The initial angular position is set at 20 deg. External force was applied to the miniature robot finger, and the rotation angle of the joint was recorded at each force interval.

Figure 14 shows the results of the stiffness control experiment. To adjust the average voltage, the duty ratio of PWM was controlled. And, by adjusting the average voltage the rotation angle of the joint changes when external force is applied. This is based on the temperature-tension relationship of SMA wires. When voltage applied is increased, the temperature of SMA wires will rise. The tension of SMA wire will also increase in connection with the temperature change. As shown above, we confirmed that stiffness of joint of miniature robot finger can be controlled by changing the tension of SMA wires.

4. Conclusion

In this paper, we have developed a 1/4 scaled miniature robot finger with a variable stiffness mechanism using SMA, and confirmed its usefulness through experiments as the first step of the development of a robot hand. First, we proposed the driving mechanism of the robot finger. The driving mechanism uses SMA instead of electromagnetic motors. The structure of the robot finger imitates the musculo-skeletal system of humans, since SMA wires exhibit nonlinear features similar to human muscles. Generated force of SMA wires is proportional to area. These features are effective for miniaturization. Furthermore highly precise position control of the fingertip is performable by using SMA and an encoder. Strain gages were used to measure the generated force. Each strain gage is bonded to a small copper plate and is arranged at the end of SMA wires. The tension of SMA wires was measured by a strain gage and generated force was controlled. We confirmed that it is possible to change the stiffness of the finger joint by heating the two SMA wires, and generating tension simultaneously. Furthermore, the response of SMA was improved by using SMA wires small in diameter.

In following studies, we will realize arbitrary stiffness control of the finger joint by modeling the nonlinear characteristics of SMA. We also plan to develop a miniature robot hand by using the proposed driving method

5. Acknowledgment

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