Design of a Functional Prosthetic Hand for Children using Novel Shape Memory Alloy Actuators

Hironari Taniguchi
Department of Electronics and Control Engineering
National Institute of Technology, Tsuyama College, 624-1, Numa, Tsuyama-city, Okayama, Japan

Atsunori Hashimoto
Advanced Mechanical and Control System Engineering
National Institute of Technology, Tsuyama College, 624-1, Numa, Tsuyama-city, Okayama, Japan

Syunsuke Izuhara
Department of Electronics and Control Engineering
National Institute of Technology, Tsuyama College, 624-1, Numa, Tsuyama-city, Okayama, Japan

Abstract- Artificial arms for children are expected to assist in their growth by helping brain growth and improving body functions. This paper describes the development of externally powered prosthetic hands for children. We focused on shape memory alloy (SMA) actuators as the drive source of the hand, because the hand requires features such as a small size, silent operation, and low mass. However, the response of SMA is relatively slow, being limited by the speed with which the SMA can be heated and cooled. Therefore, we have developed a novel SMA actuator. This actuator has a forced cooling mechanism using a fluorine-based inert liquid. We confirmed that the movement of the artificial arm occurs through the normal range of finger motion. The extension movement is performed for about one second.

Keywords – SMA Actuator, Prosthetic Hand, Children

I. INTRODUCTION

Recently, externally powered prosthetic hands are being developed worldwide for the purpose of everyday activities and social rehabilitation of people who have lost an arm in an accident or because of illness [1, 2]. The hands are being designed to improve their life quality. Externally powered prosthetic hands for children assist a child’s growth by, for example, nurturing the brain upon stimulation from both hands, improving balance, and incorporating prosthetic limbs in the body image. Moreover, it is easy to introduce the artificial arm at later stages of growth [3]. In Japan, cases of artificial arms for infants [4, 5] and pediatric prosthetic hands made in foreign countries have been reported. In these cases, the choice of a proper artificial arm is desired to ensure appropriate growth of children.

However, the hands for children are heavier than other prosthetic hands for adult size, their operability is low, and lack of capacity, discomfort, or function failure have been reported. Therefore, the hand for children which is small, light, and functional is required. Furthermore, for everyday use, low noise generation is desired during the hand moves. Accordingly, the general-purpose actuators such as motors used in externally powered prosthetic hands for adults are unfavorable drive sources for the hands designed for children.

In this study, we developed an externally powered artificial hand for infants using a shape memory alloy (SMA) actuator, which has a silent drive, small size, and high output power. The development of an artificial arm using SMA as the driving source has been already reported [6, 7]. We also have developed an externally powered prosthetic hand for children, enabling the movement of the forearm, wrist, and fingers [8]. Consequently, the movement of finger was achieved normal range of motion, but could not work consecutively because the low responsiveness of the SMA. Therefore, to solve this problem, we have developed an SMA actuator equipped with a cooling mechanism. In this paper, we describe the structure of an externally powered prosthetic hand for children incorporating a cooling type SMA actuator and report on the gripping force of the device.

II. INERT FLUID COOLING TYPE SMA ACTUATOR

A. Structure

In the cooling type SMA actuator, the container holding the SMA is filled with fluorine based inert liquid with excellent electrical insulation and heat transfer properties as a refrigerant. This liquid is subjected to heat radiation generated from the SMA to improve the responsiveness. To completely seal the vessel and circulate the refrigerant, the container is made of a flexible material capable of driving while being deformed. Figure 1 shows the three-dimensional CAD structure of the cooling type SMA actuator.

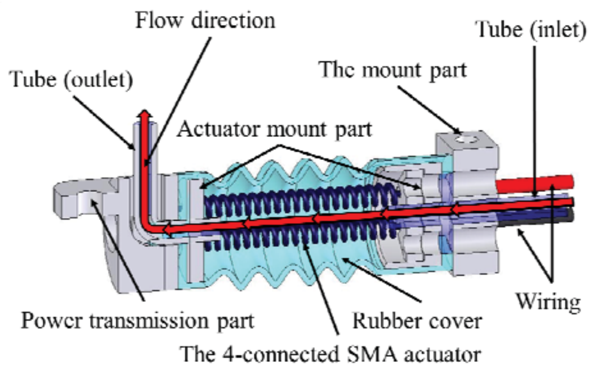

Figure 1. Structure of the cooling type SMA actuator

The cooling type SMA actuator consists of coiled SMA wires, a rubber cover, a tube, a device mount part, a drive transmission part and wiring. The coiled SMA wire contains four connections from one SMA wire to achieve a reduction in size and weight of the equipment. The SMA wire which is fixed into a coil using a special jig was heated for 45 min at 450°C using an electric furnace and then water was used to achieve the shape memory through rapid cooling. The SMA is composed of a nickel–titanium alloy containing 55.19% Ni. The shape recovery temperature used was about 65°C. Table 1 shows the specifications of the coiled SMA. Figure 2 shows the dimensions of the SMA. The rubber cover, which is composed of silicone rubber (Product made in Shin-Etsu Silicone Co., Ltd.: KE-1603) with a good dimensional stability and liquidity, was deformed at the time of driving to adopt a bellows structure, which does not interfere with the drive. Furthermore, the connection with the tube was sealed by integral molding. The tube has an inner diameter of 1.0 mm and an outer diameter of 2.0 mm. The fluorine containing inert liquid inflow from the mount part side is discharged from the drive transmission unit side after passing through the rubber cover. The volume of the rubber cover is 1400 mm^3 and the maximum flow rate that could be supplied to the actuator is 0.35 ml/s.

Figure 3 shows the dimensions of the cooling type SMA actuator. The total length of the cooling type SMA actuator is 42 mm and it becomes 32 mm after shrinking. In addition, the mount part has a squared shape with 11 mm long sides. The rubber cover is cylindrical with the periphery of the mounting portion being 10 mm in diameter. The maximum outer diameter of the drive part is 11 mm and the minimum is 9 mm, whereas the pitch of the bellows is 3 mm. The thickness of the rubber is 0.5 mm.

Table 1 Specifications of the SMA

Diameter of SMA wire [mm]	0.5
Diameter of coiled SMA [mm]	1
Number of the winding	20
Length [mm]	20
Stroke [mm]	10

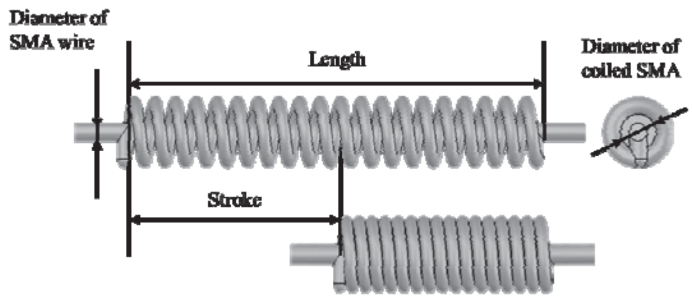

Figure 2. Dimensions of the coiled SMA wire

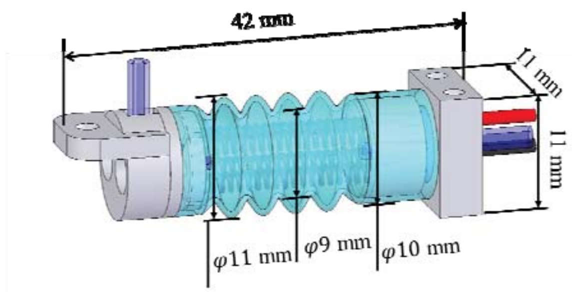

Figure 3. Dimensions of the cooling type SMA actuator

B. Drive principle

The cooling type SMA actuator is driven by the shape memory effect due to Joule heating, in which the heat is generated by applying an electric current. After driving the SMA, the rubber cover, which is positioned in the refrigerant, dissipates the heat of the SMA by circulating the refrigerant with a pump. The cooling type SMA actuator designed in this study is attached to an external reconstruction system. The reconstruction mechanism used a spring for reconstruction. The drive principle is summarized as follows;

① The initial state of the cooling type SMA actuator is extended by the restoring mechanism.

② By applying an electric current to the cooling type SMA actuator, Joule heat is generated and the SMA is operated.

③ The coiled SMA generates a contractile force. If the contractile force exceeds the reconstruction force, the actuator shrinks while deforming the rubber cover.

④ By stopping the application of the electric current, the force generated by the cooling type SMA actuator is reduced and returns to the initial state through the reconstruction force. At this time, by performing forced cooling, the reconstruction speed of the return process is faster than the cooling by natural heat dissipation.

III. Functional Prosthetic Hand for Children

A. Structure

The holding operation that can be performed by a human hand is divided into two distinct kinds. The first operation consists of wrapping an object across the palm (i.e., grip action), and the second one consists of having a gripping target at the tip of the middle finger, index finger, and thumb (i.e., pinch action). The basis of the holding operation consists of both these kinds of operation. In the case of a high-performance artificial arm, training from childhood enables smooth performance of the holding action. Therefore, the gripping action of pediatric prosthetic hands can be developed to have both types of operation.

The size of the functional prosthetic hand for children was assumed to be that of a six-year-old child. The child has the intellectual ability to understand instructions at that age. Furthermore, considering the esthetic side, the device was designed to be covered with a decorative glove for use by a six-year-old. Figure 4 shows the image of the cooling type SMA actuator incorporated in the externally powered prosthetic hand for children.

This externally powered prosthetic hand for children has two cooling type SMA actuators. As shown in Figure 4, the actuators are fixed to the drive transmission plate with the reconstruction spring in the middle. The drive transmission board is connected to each finger except the thumb through a link. By operating the drive transmission plate with the SMA actuator, the fingers other than the thumb are moved. The drive principle is described as follows:

□ In the initial state, the drive transmission board pushes the link as shown in Figure 4, through the spring for reconstruction and the finger is maintained in the closed state.

② When the cooling type SMA actuator is driven, the drive transmission board and link are pulled. At this time, the force generated by the cooling type SMA actuator exceeds the force generated by the spring for reconstruction, the drive transmission plate is moved while compressing the spring (Figure 5), and the fingers are extended. To maintain the extended state, it is necessary to continue driving the actuator.

③ If the drive of the actuator is stopped, the fingers start bending under the elastic force of the spring for reconstruction. At this time, by performing forced cooling, the heat of the SMA is heat radiation, and the force generated by the actuator suddenly decreases. Consequently, it is possible to immediately return to the state in Figure 6.

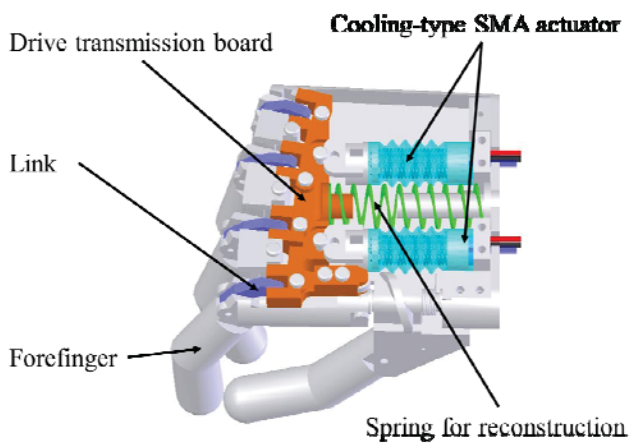

Figure 4. Structure of the artificial arm for children

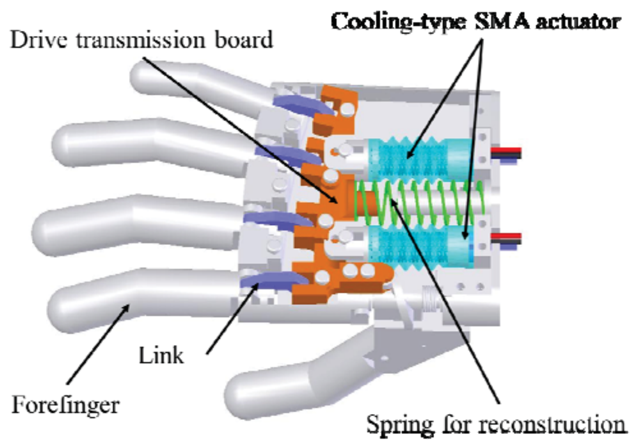

Figure 5. Structure of the artificial arm for children (open)

B. Gripping force

To determine the gripping force of the externally powered prosthetic hand for children, we performed an experiment to evaluate the force of the cooling type SMA actuator. Figure 6 shows the schematic of the experimental setup. Two actuators were used like in the artificial arm, and they were extended up to the maximum length of 42 mm. In addition, the fluorine containing inert liquid filling the interior of the actuator was EF-L174, which was manufactured by Mitsubishi Materials Electron Chemicals Co., Ltd. The driving of the actuator was performed by applying direct electric current at 0.5 A increments from 1.5 A to 2.5 A. If the direct electrical current is used more than 3.0 A, SMA actuator is too hot and gets broken.

The experimental results are shown in Figure 7 and Table 2. From the experimental results, we recognized that the generated force increases with an increase in current. In addition, the generated forces were increased approximately linearly. The generated force of 2.0 A is almost twice higher than that suggested by the result of 1.5 A. Therefore, if a large gripping force is obtained, it is necessary to flow a large current.

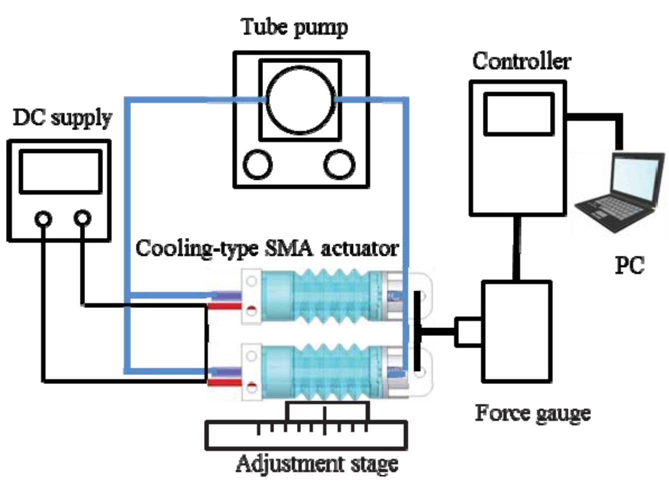

Figure 6. Experimental schematic diagram

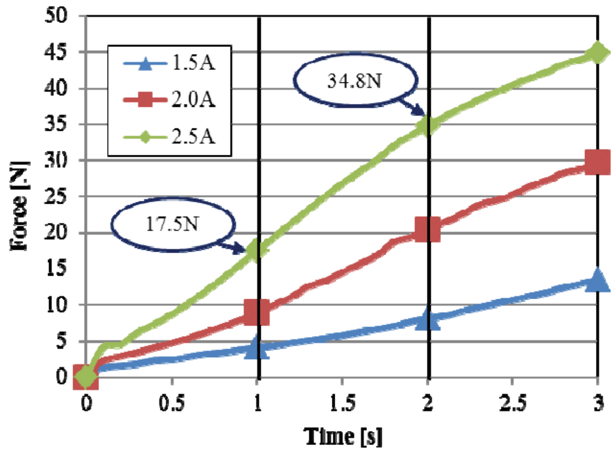

Figure 7. Forces generated in the experiment

Table 2 Results of experimental

Current value [A]	Force [N]		
	1 second later	2 second later	3 second later
1.5	4.1	8.1	13.4
2.0	8.9	20.5	29.8
2.5	17.5	38.4	44.9

According to the artificial limb production company, the movement speed of the externally powered prosthetic hands is from 1.0 to 2.0 seconds in general. In the experiment, when applying an electric current of 2.5 A in 1.0 s, a generated force of about 18 N was obtained, whereas in 2.0 s, a generated force of about 35 N was obtained. To operate the externally powered prosthetic hand, it is required to exceed the force of the restoring spring. A desirable gripping force is about 10 N, which would enable most of the actions performed by children, such as holding dishes or changing clothes. Thus, the gripping force of the externally powered prosthetic hand for children was 10 N. In addition, because a high operation speed is preferred, we aimed to perform such operations in 1.0 s.

IV. Conclusion

In this paper, we described the structure of an externally powered prosthetic hand for children incorporating a cooling type SMA actuator. The cooling type SMA actuator, which employs a fluorine-based inert liquid as a refrigerant, possesses higher responsiveness than that of a conventional SMA actuator by controlling the heat necessary for drive of the SMA. Here, we developed a cooling type SMA actuator prototype for externally powered prosthetic hands for children and confirmed that the force generated is about 20 N in 1.0 s and about 35 N in 2.0 s. From these results, the gripping force of the externally powered prosthetic hand for children was determined to be 10 N, which was targeted to operate in 1.0 s. In the future, the actuator will be incorporated in externally powered prosthetic hands for children, and the movement performance will be evaluated. In addition, we will test the power of a pediatric prosthetic hand incorporating a peripheral device to be used for cooling the actuator and drive controller.

V. ACKNOWLEDGMENTS

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