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Investigation of a gripping device actuated by SMA wire

Z.W. Zhong*, S.Y. Chan

School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Republic of Singapore

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Abstract

A gripping device actuated by shape memory alloy (SMA) wire was fabricated and investigated. The actuation mechanism and the working principle of the gripping device are simple. A SMA wire was used to close the gripper during operation and a torsion spring was integrated to open the gripper when the SMA wire relaxed. Several experiments were conducted to investigate the performance of the gripping device. The aspects investigated include gripping force, response time and cyclic test number of the gripping device. It was found that factors such as driving current, torsion-spring torque, SMA wire diameter and the number of coils the SMA wire was wound had significant effects on the gripping device's performance. The gripping force was adjustable by changing the driving current. The gripping device using one coil of Ø 100 μm SMA wire with a music wire spring produced good performance and the gripping device could withstand over 1.175 million opening and closing cycles without any deterioration in its performance.

Keywords: Gripper; Shape memory alloy; Actuator; Force sensor

1. Introduction

Although considerable developments have been achieved in fabrication of micro systems [1–4], the assembly of these systems still accounts for a substantial portion of the final cost. One basic challenge in micro-assemblies is the demand for very high accuracy over a large range of motion [5].

Various prototypes of micro-grippers using different types of actuators such as electro-thermal actuators [6], electrostatic actuators [7], electromagnetic actuators [8] and shape memory alloy (SMA) actuators [9] have been developed. Piezoelectric actuators are widely used in various applications [10–20] and also in micro-grippers [21].

A typical micro-gripper is made of stainless steel or thin-plate silicon, designed as a compliant mechanism so that conventional bearings are replaced by flexure hinges, which are regions with decreased stiffness [22]. The actuation is typically provided using a SMA foil (laser-cut and mounted on the gripper [22,23] or surface-deposited [24]) or a piezoelectric actuator.

For example, a silicon micro-gripper with SMA actuation was developed [25]. The gripper jaws were two cantilever beams. Ni–Ti–Cu SMA thin films were deposited on the bottom and top surfaces of the gripper to generate high-force low-temperature actuation to open the jaws.

Another example is a SMA micro-gripper with integrated position sensing and actuation functions [26]. This system had a monolithic device micro-fabricated from a SMA thin sheet. The device had two actuators with opposite actuation directions, allowing on/off operations between closed and open positions.

A SMA wire actuated gripping device was also test-fabricated using a conventional milling machine [27]. The mechanism of this device was able to convert the linear motion of the SMA wire displacement into the angular motion of gripper jaws.

Shape memory effect [28] is a phenomenon that after a SMA is deformed below the austenite start temperature, it can recover the memorized shape when it is heated to a temperature above the austenite finish temperature. This effect is due to the presence of the reversible martensitic transformation between a high-temperature austenite phase and a low-temperature martensitic phase.

SMAs have also been used in dental and medical applications [29]. Conventionally, vascular stent was made of stainless steel and was expanded along in the artery using a plastic balloon.

* Corresponding author. Tel.: +65 6790 5588; fax: +65 6791 1859.
E-mail address: mzwzhong@ntu.edu.sg (Z.W. Zhong).

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Recently, NiTi shape memory alloys were used to replace stainless steel as the materials of vascular stents [30]. SMAs are also commonly used to make couplings for joining pipes and tubes [31].

This study focused on the investigation of the performance of a gripping device actuated using SMA wire. Experiments were conducted to examine the effects of several factors on the performance of the gripping device. These factors were the driving current, spring torque, SMA wire diameter and number of coils the SMA wire was wound. The performance of the gripping device investigated included the gripping force, the response time of the gripper and the cyclic number of opening and closing operations.

2. Design of the gripping device

Fig. 1 shows the overview of the design. The gripper consists of one movable gripping jaw (left jaw) and one fixed jaw (right jaw). The dimensions of the gripper are 12 mm (*W*) × 8 mm (*H*) × 28 mm (*L*). With the driving circuit board integrated, the overall dimensions of the whole device are 28 mm (*W*) × 19 mm (*H*) × 89 mm (*L*).

The right jaw is fixed onto a base plate using screws while the movable left jaw is mounted onto the base plate using a rivet to allow the left jaw to rotate with respect to the rivet and the right jaw, and as a result opening and closing operations of the gripper can be achieved. The two ends of the SMA wire are connected to a circuit board, which provides electrical driving current to heat the SMA wire during the gripping operation. Small grooves are created on the gripping surfaces of both gripper jaws for the purpose of generating sufficient surface roughness and friction on the griping surfaces, so that slippage of the object being griped can be avoided.

A torsion spring is integrated in the gripper to open the gripper while the closing of the gripper is performed by the SMA wire. Thus, the advantage of using a SMA material is utilized to grip an object, instead of opening the jaws. The torsion spring used for opening the gripper can be small because it is used to pull the relaxing SMA wire through the movable gripping jaw. By having one fixed jaw, users can first bring this fixed jaw close to the object to be gripped, and then the movable gripping jaw is closed. The gripping accuracy can be enhanced [32] because the gripping position can first be fixed before the object is gripped firmly.

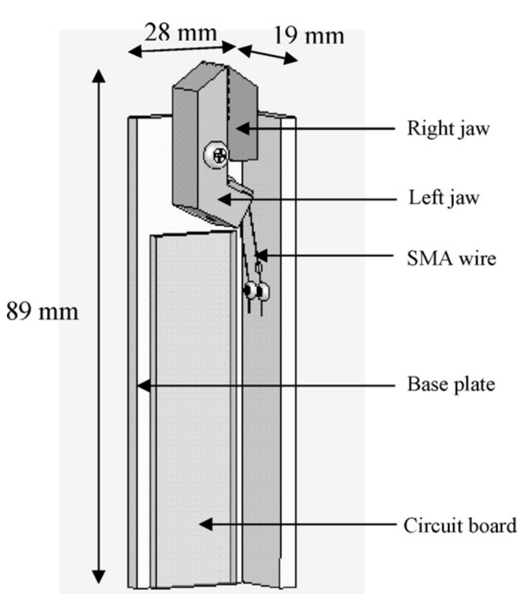

Fig. 1. Overview of the design.

3. Experiments

A prototype of the gripping device was fabricated to investigate its performance. The jaws were made of stainless steel, and the base plate was made of Acrylic. The jaws were dimensionally small, and therefore were designed by us but fabricated by a sub-contractor. The base plate was fabricated by us through sawing, drilling and tapping. Acrylic is easy to be machined, and it functions as an insulation material to have the SMA wire and electronic circuit parts interconnected on it. Both ends of the SMA wire were secured to the base plate by two screws, which could provide quick, easy, adjustable and reliable connections and permit easy change of wires for testing purposes. An oscillator circuit using a small plastic package of a 555 integrated circuit (timer) was adopted to support the actuation of the SMA wire without overheating it.

Three experiments, namely gripping force measurement, response time measurement, and cyclic test, were conducted to investigate the performance of the gripping device.

3.1. Gripping force measurement

A force sensor (Tekscan Flexiforce A201) was used to measure the gripping force. This sensor [33] is an ultra-thin film with a thickness of 0.127 mm. The active sensing area has a 9.53-mm diameter. The force sensor acts as a variable resistor in an electrical circuit. When the force sensor is unloaded, its resistance is very high (greater than 5 MΩ). When a force is applied to the sensor, this resistance decreases. The resistance change can be read by connecting an ohmmeter to the sensor and applying a force to the sensing area.

Calibration was performed to relate the output resistance of the sensor to the gripping force imposed by the gripper. Known weights with different values ranging from 20 to 500 g were used in the calibration. A calibration equation was obtained based on a set of data taken.

Then, the force sensor was placed in between the gripper jaws. When it was heated by driving current, the SMA wire shortened and pulled the left jaw to close. Hence, the gripper was closed and a gripping force was exerted on the sensor. A multimeter was used to measure the output resistance of the sensor. The resistance value was then converted to conductance. Thus, the value of the gripping force could be calculated from a linear graph obtained during the calibration.

3.2. Response time measurement

As discussed in previous sections, when it is heated by electrical driving current, the SMA wire shifts to the austenite

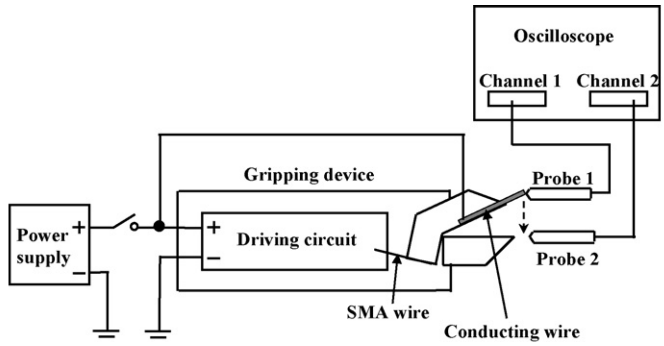

Fig. 2. Schematic diagram of the experiment setup for closing time measurement.

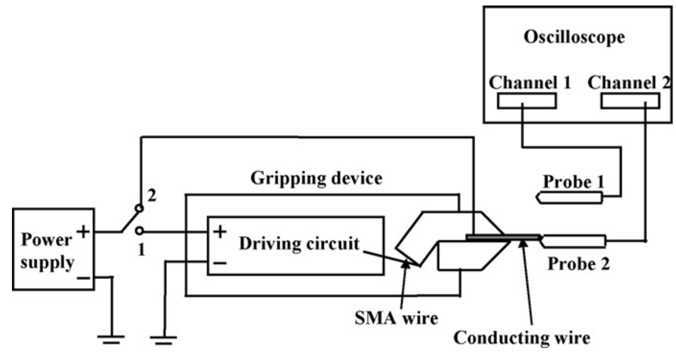

Fig. 3. Schematic diagram of the experiment setup for opening time measurement.

phase and contracts, thus closing the gripper jaws. When the current is removed, the SMA wire is cooled and shifts back to the martensite phase. With a force applied by the torsion spring, the wire elongates and the gripper jaws are opened by the torsion spring. It takes some time for the SMA wire to be heated or cooled and to complete the phase change in the jaw closing or opening operation. Therefore, two experiments were designed to determine the response time for the opening and closing operations of the gripper jaws at different driving current levels, and to investigate the effects of driving current, torsion spring torque and SMA wire diameter on the response time.

Fig. 2 shows the schematic diagram of the experimental setup designed particularly to determine the time needed to close the gripper jaws from a fully open state. A conducting wire was attached to the movable jaw. This wire was connected to the power supply and when the switch was turned on, electrical current would run through the conducting wire and at the same time, the driving circuit was activated to heat the SMA wire.

Probes 1 and 2 were placed near to the tip of the gripper jaw in such a way that the conducting wire would touch probe 1 when the gripper was fully opened. When the gripper was fully closed, the conducting wire would touch probe 2. These two probes did not restrict the movement of the gripper jaw in order to obtain an accurate reading of the closing time. This means that the conducting wire would only touch the probe and not press it. These two probes were connected to channels 1 and 2 of an oscilloscope. The closing time could be determined by measuring the time indicated between the two rising edges of the signals from channels 1 and 2 of the oscilloscope.

Fig. 3 shows the schematic diagram of the experimental setup designed particularly to determine the time needed to open the gripper jaws from a closed state. This setup had some minor modification from the closing-time measurement setup. The switch used in this experiment was a two-way toggle switch. When the switch was toggled, electrical current would only run through the conducting wire, not the driving circuit, and vice versa. The closing time could then be determined by measuring the time indicated between the two rising edges of the signals from channels 1 and 2 of the oscilloscope.

3.3. Cyclic test

The reliability of the gripping device depends greatly on the performance of the SMA wire such as how many opening and closing cycles the SMA wire can last before it snaps or loses its shape memory effect. In order to determine the reliability of the gripping device, a cyclic test was conducted. During the test, the gripper was controlled to open and close its jaws automatically and continuously. The period for each operation cycle was set to a predetermined time value. The total time for the test, T_t, was recorded and then divided by p (the period of each cycle) in order to obtain the total number of cycles, n, as expressed by Eq. (1).

$$n = \frac{T_t}{p} \tag{1}$$

4. Experimental results and discussion

4.1. Gripping force

A few factors were considered to have effects on the gripping force. They are torsion spring torque, diameter of the SMA wire and number of coils of the SMA wire wound.

The gripper was designed to have five protruded pins on the left jaw to allow the flexibility of winding the SMA wire around the pins. As such, the effect of the number of SMA wire coils on the gripper performance could be studied by changing the number of coils wound around the pins.

Fig. 4 shows gripping forces versus driving current measured using the gripping device with a music wire spring and a Ø 100-μm SMA wire (MONDO•TRONICS Flexinol 100LT) that was wound one time (one coil) or two times (two coils). With a constant voltage applied to the SMA wire, increasing the driving current would increase the power consumed by the SMA wire. Therefore, the gripping force increased linearly with increasing driving current. Moreover, the gripper was subjected to a larger force with more wire coils. Therefore, the gripping force increased as the number of wire coils increased.

However, many coils of SMA wire would cause a negative effect on the gripper performance. The SMA wire needed a long time to be activated. This was because the longer the wire, the more time was needed to allow the current to heat the long wire

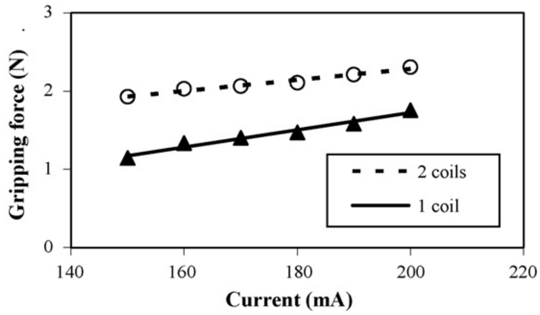

Fig. 4. Gripping forces vs. driving current measured using the gripping device with a music wire spring and a Ø 100-μm SMA wire that was wound one time (one coil) or two times (two coils).

before it contracted. Therefore, all the experiments reported in the rest of this article were conducted using only one coil of SMA wire.

The effect of the torsion spring torque on the gripping force was investigated using two types of torsion springs made of different materials with known spring torque values. The springs were a music wire torsion spring (Shincoil SST-017C-1-R-M, torque = 1.44 kg mm) and a stainless steel torsion spring (Shincoil SST-017C-1-R-S, torque = 1.20 kg mm) [34].

Fig. 5 shows gripping forces versus driving current measured using the gripping device with a Ø 100-μm SMA wire and a music wire spring or a stainless steel spring.

The experiment was started from giving a driving current level of 100 mA. However, the Ø 100-μm SMA wire could not be activated at such a low current level. It could only be activated with the minimum input current of 150 mA. There is also a current level, known as recommended current level, which activates but not quickly overheats the SMA wire in still air at room temperature [35]. The recommended current level for the Ø 100-μm SMA wire is 200 mA specified by the manufacturer. Therefore, the experiment stopped at the current level of 200 mA.

Again, the gripping force increased linearly with increasing driving current, as shown in Fig. 5. The gripper with a music wire torsion spring had smaller gripping forces at all current levels compared to the gripper with a stainless steel torsion spring. This was due to the larger torque of the music wire spring, which caused a larger resistance to the closure of the gripper jaws, and consequently the net gripping force became smaller.

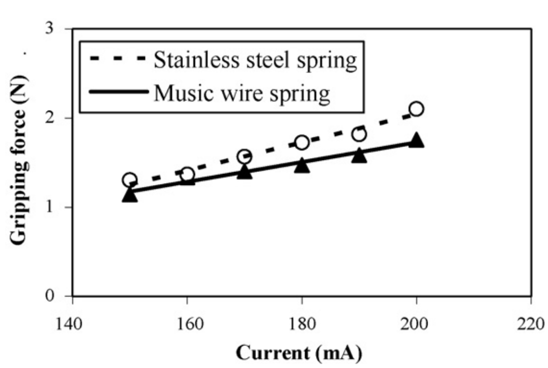

Fig. 5. Gripping forces vs. driving current measured using the gripping device with a Ø 100-μm SMA wire and a music wire spring or a stainless steel spring.

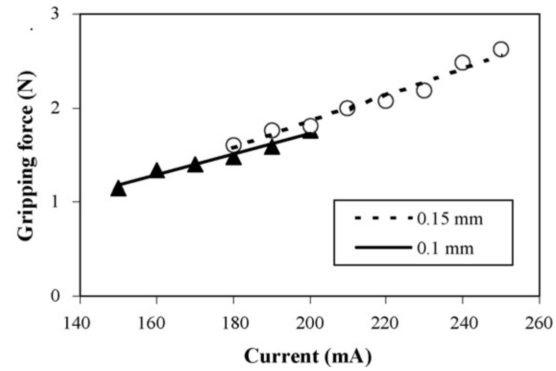

Fig. 6. Gripping forces vs. driving current measured using the gripping device with a Ø 0.1-mm or Ø 0.15-mm SMA wire and a music wire spring.

To study the effect of wire diameter on gripping force, two SMA wires with diameters of 100 and 150 μm (MONDO• TRONICS Flexinol 150LT) were tested as the actuator of the gripper.

Fig. 6 shows gripping forces versus driving current measured using the gripping device with a Ø 100-μm or Ø 150-μm SMA wire and a music wire spring. Similar to the trends shown in Figs. 4 and 5, the gripping force increased with increasing driving current. However, the Ø 150-μm SMA wire could only be activated when the current reached 180 mA. This is because a thicker wire has a larger volume. Hence, more current and power are needed to heat the wire entirely and activate it to contract. The recommended maximum current level for the Ø 150-μm SMA wire is 400 mA [35]. Therefore, the current level of the experiment for the Ø 150-μm wire could be extended beyond 200 mA (maximum for the Ø 100-μm wire) to 250 mA. As shown in Fig. 6, a thicker SMA wire produced a higher gripping force compared to a thinner SMA wire.

4.2. Response time

The driving current applied may be the main factor affecting the speed at which the SMA wire contracts and relaxes. Besides, the spring torque and the diameter of the SMA wire may also affect the response time of the gripper. Therefore, experiments were conducted to study the effects of these three factors on the response time.

Fig. 7 shows closing time and opening time of the gripping jaws versus driving current measured using the gripping device with a Ø 100 μm SMA wire and a music wire spring or a stainless steel spring.

As shown in Fig. 7, the closing time of the jaws decreased with increasing driving current. This was because as the current was increased, more power was supplied to the SMA wire. Hence, the wire was heated to start contraction in a shorter time. It can also be seen that the closing time for the gripper with the music wire spring was slightly longer than that with the stainless steel spring. This was because the slightly larger torque of the music wire spring resulted in a larger resistance to the closing operation, causing the gripper to take a slightly longer time to close completely.

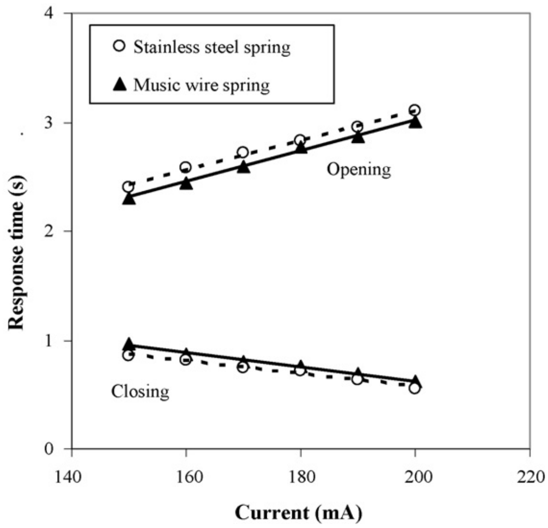

Fig. 7. Closing time and opening time vs. driving current measured using the gripping device with a Ø 100-μm SMA wire and a music wire spring or a stainless steel spring.

On the other hand, the opening time was much longer than the closing time, because it took more time for the SMA wire to be cooled than to be heated. When the driving current was increased, the opening time of the jaws also increased. This was because a longer time was needed to dissipate the heat from the SMA wire after more power was supplied to it. In other words, the rate at which the SMA wire could relax depended on how fast the wire was able to cool and dissipate the heat when the current was removed. As the current increased, more heat was supplied to the wire. Therefore, it needed a longer time to dissipate heat generated by the increased current. In addition, the opening time for the gripper with the music wire spring was slightly shorter than that with the stainless steel spring. This was because the music wire spring had a slightly larger torque and therefore was able to open the gripper in a slightly shorter time.

Fig. 8 shows closing time and opening time of the gripping jaws versus driving current measured using the gripping device with a Ø 100-μm or Ø 150-μm SMA wire and a music wire spring. Similar to the results shown in Fig. 7 with the same reasons, the closing time decreased but the opening time increased with increasing driving current for both SMA wire diameters.

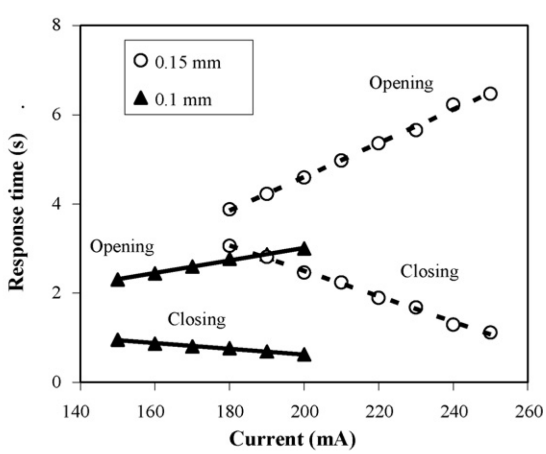

Fig. 8. Closing time and opening time of the gripping jaws vs. driving current measured using the gripping device with a Ø 0.1-mm or Ø 0.15-mm SMA wire and a music wire spring.

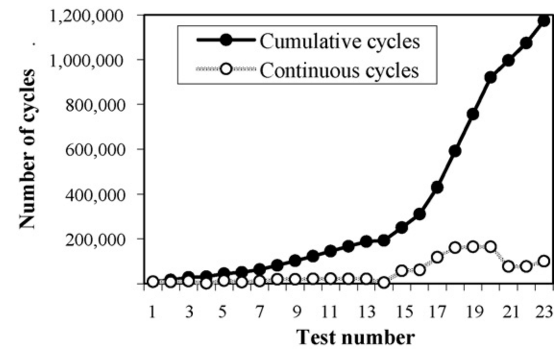

Fig. 9. Number of open-close cycles vs. test number of the cyclic test.

Fig. 8 also shows that a thinner SMA wire needs less time to close the gripper. This is because a thinner wire has smaller volume, and hence requires a shorter time to heat the entire wire length. Besides, the gripping device with a thinner SMA wire also needs less time to open the jaws fully. A SMA wire with a smaller diameter has a smaller volume and it cools faster than a thicker SMA wire, because it has less heat to dissipate.

4.3. Cyclic test result

The gripping device using one coil of Ø 100-μm SMA wire and a music wire spring was used to run the cyclic test to examine the reliability of the device. The test was conducted continuously with short periods of stops so that the performance of the gripping device could be inspected. However, the SMA wire was found snapped after the gripping device had run for 20,800 cycles. It was found that the sharp edge of the left jaw where the SMA wire was wound around caused the failure of the wire. The sharp edge rubbed the wire during the operation of the device and hence caused the wire to break.

This problem was resolved by rounding the sharp edge using a grinding paper to obtain a round and smooth corner. The test was re-conducted using a new Ø 100-μm SMA wire. Fig. 9 shows the number of open-close cycles versus the test number of the cyclic test. The gripping device could withstand over 1.175 million cycles without any failure. After the test, the performance of the gripping device was inspected again by measuring its gripping force and response time, etc. The outcome of these inspections confirmed that the performance of the gripping device was consistent with the results that were obtained before the cyclic test.

5. Conclusion

As our contributions in this study, several experiments were conducted to investigate the effects of several factors on the performance of the gripping device actuated using SMA wire. Experimental setups were particularly designed to determine the time needed to close or open the gripper jaws from a fully open or closed state. The results are promising in terms of the consistency and reliability of the device. The reasons for the findings are explained. They are useful for further improved design and fabrication of micro-grippers for various applications.

It was found that factors such as driving current, spring torque, SMA wire diameter and the number of coils the SMA wire was wound had significant effects on the gripping device's performance. The gripping force increased with increasing driving current, wire diameter and number of coils, but decreased with increasing spring torque. The closing time of the gripper decreased with increasing current but increased with increasing wire diameter. The opening time increased with increasing current and wire diameter. The gripping force was adjustable by changing the driving current. The gripping device using one coil of Ø 100-μm SMA wire with a music wire spring produced good performance and the gripping device could withstand over 1.175 million opening and closing cycles without any deterioration in its performance. The actuator (SMA wire) costs only about US$ 1.45, much less-expensive than other actuators such as piezoelectric actuators.

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Biographies

Z.W. Zhong Dr. Zhong worked at the Institute of Physical and Chemical Research, Japan, after he received his doctor of engineering in precision engineering in 1989. He has also worked at the Gintic Institute of Manufacturing Technology, Singapore, and is currently at the Nanyang Technological University, Singapore. His research and development areas are microelectronics packaging, precision engineering, mechatronics and design.

S.Y. Chan Miss Chan received her bachelor of engineering in mechanical and aerospace engineering (honour) from Nanyang Technological University in 2006. Currently, she is pursuing a career as a teacher to realize her dream of imparting knowledge to the younger generation.