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# Development of a shape-memory-alloy micromanipulator based on integrated bimorph microactuators

Alaa AbuZaiter, Marwan Nafea, Mohamed Sultan Mohamed Ali*

*Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia*

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ABSTRACT

This paper reports a novel structure of a shape-memory-alloy (SMA) micromanipulator with gripping mechanism. A featured integration of multiple SMA bimorph microactuators has been utilized to form a micromanipulator with three degrees of freedom. The design consists of two links (SMA sheets) and a gripper at the end of the second joint. The overall dimensions of the micromanipulator are 33 mm × 9 mm × 3 mm. The displacement of each actuator is controlled by a heating circuit that generates a pulse-width modulation signal. Theoretical modeling of SMA actuators is studied and verified with simulation. The SMA micromanipulator is able to move in the *x*- and *y*-axis by 7.1 mm and 5.2 mm, respectively, resulting in a maximum displacement of 8.9 mm. The micro-gripper has a maximum opening gap between its fingers of 1.15 mm. The micromanipulator has a temporal response of 7.5 s and 9 s for its *x*- and *y*-axis. The maximum actuation force generated by the *x*- and *y*-axis was around 100 mN and 130 mN, respectively. The developed micromanipulator has been successfully used to move a small object.



## 1. Introduction

Micromanipulators have been widely applied in various applications, especially in those requiring high-precision coordination and delicate handling of micro objects in a very limited space. Several manipulators have been developed and reported for micro handling in recent decades [1–3], however, most of these manipulators use servomotors and [2] direct current (DC) motors [3] for their operation, resulting in a relatively large device structure that is indeed not suitable for applications in microenvironments. Recently, the use of microelectromechanical system (MEMS) technology has enabled the manufacturing of a wide range of miniaturized micromanipulators using microfabrication techniques. These MEMS-based micromanipulators utilize several actuation mechanisms, including electrostatic [4], electromagnetic [5], and piezoelectric actuators [6]. Despite having small device structures, high accuracy and fast response times, these micromanipulators often suffer from a limited displacement range, a low actuation force, and difficulties related to the fabrication process [7]. Using shape-memory-alloy (SMA) microactuators could potentially be a good solution that addresses the issues associated with the aforementioned actuators in the development of micromanipulators. SMA microactuators provide higher work density, displacement, and actuation force compared with the other actuation mechanisms [8–10]. Moreover, SMA microactuators possess various advantages, including a simple mechanical structure, corrosion resistance, and biocompatibility [11,12]. The proposed MEMS-based SMA microactuator mainly includes nickel and titanium alloy (nitinol). The composition level between these two metals will essentially determine the transformation temperature. Thus, the composition can be intentionally changed in order to achieve a specific transformation temperature. This offers high flexibility and various choices for the application of SMA microactuators in various contexts depending on the suitable temperature range (from −50 °C to 110 °C) [13]. Due to these advantages, SMA microactuators have been widely utilized in several applications, especially in biomedical fields [14]. SMA-based micromanipulators have been reported by several researchers [15–20]. In a previous study, Lim et al. reported a catheter that consists of multiple SMA actuators attached to micromachined ring links and bias springs to achieve a multi-directional bending motion [21]. However, this device requires a complicated fabrication process and suffers from a low accuracy. Mineta et al. reported an active guide wire that consists of an SMA wire actuator with a meandering shape and a bias coil spring [22]. The SMA wire and the bias spring coil were covered with a thin polyurethane tube. The structure was able to bend in one direction through heating with an electrical current, while it was restored by the bias coil. However, the device can be operated in limited degrees of freedom (DOF). This concept was further improved later by Mineta

* Corresponding author. fax: +6 07 5566272.
*E-mail address:* sultan_ali@fke.utm.my (M.S. Mohamed Ali).

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et al. [18], where three meandering springs and joint rings were fabricated from an SMA tube. The springs were extended and fitted to a tubular bias mechanism. Each spring was individually heated by an electrical current, causing the spring to shrink to its original shape. However, the actuation range of this device was limited. Another concept of SMA micromanipulators has been proposed by Lan et al. [23]. their reported design was a rotary manipulator that is based on SMA wire actuated flexures. A bi-directional motion was achieved by connecting two parallel micromanipulators, where each of them is being actuated in the opposite direction using a corresponding SMA wire. However, this micromanipulator suffers from its large size and low degree of freedom (DOF).

This paper reports the design and fabrication of a novel micromanipulator with gripping mechanism driven by SMA actuators. The structure is achieved by integrating a sequence of SMA bimorph microactuators to form the micromanipulator. This integration technique addressed the previously discussed SMA-based micromanipulators; it ensures achieving high displacement and multiple DOF while, at the same time, preserving the simplicity of both the device fabrication and actuation method in order to attain miniature structure. The micromanipulator consists of two links and a gripper at its end, where the two links allow the micromanipulator to move in two directions ($x$- and $y$-axis) and the gripper is utilized for manipulation of small objects. To control the micromanipulator, the SMA bimorph microactuators are controlled using a pulse-width modulation (PWM) signal that is generated by a heating circuit. Thermodynamic modeling of SMA actuators is studied. The design and working principle of the developed SMA micromanipulator, including finite element analysis (FEA) of the thermomechanical behavior of the SMA actuators, is presented. Moreover, the fabrication process of each part of the developed micromanipulator, as well as the design of the heating circuit, is discussed. In addition, the experimental results obtained from this investigation are presented and discussed along with the proposed applications.

## 2. Design and working principle

The actuation of the SMA material depends on the change of the crystal phase between the martensitic and austenitic phases. This phase change can be achieved by changing the temperature of the SMA, either through an internal or external heat [24]. Using an SMA material in bimorph actuators offers a higher force while a lower temperature is required to reach to the fully-actuated state (austenitic phase) compared to other materials that require a higher temperature to be fully-actuated [25].

The design of the SMA micromanipulator has been developed by combining two SMA bimorph microactuators with a phase angle difference of 90° to create the two links of the micromanipulator. Following this, a gripper that consists of two SMA bimorph microactuators is connected to the end of the second link. The two SMA links displace the gripper along the $x$- and $y$-axis, while the fingers of the gripper can be opened and closed to pick small objects. Fig. 1(a) illustrates the initial state of the micromanipulator when it is not being actuated. The two links and the gripper are connected to a heating circuit that generates a PWM signal to control the displacement of the micromanipulator. Fig. 1(b) shows the micromanipulator when it is fully-actuated, leading the two links to be straightened and the gripper to be opened. The overall dimensions of the micromanipulator are (33 mm × 9 mm × 3 mm), while the dimensions of the links, joints, and the gripper are as described in Table 1.

The SMA links are formed based on the difference in the coefficient of thermal expansion (CTE) between the SMA material (6–11 $\mu m \cdot m^{-1} \cdot °C^{-1}$ depending on the temperature) and the stress layer (2 $\mu m\, m^{-1}\, °C^{-1}$ for silicon dioxide ($SiO_2$) used in this study)

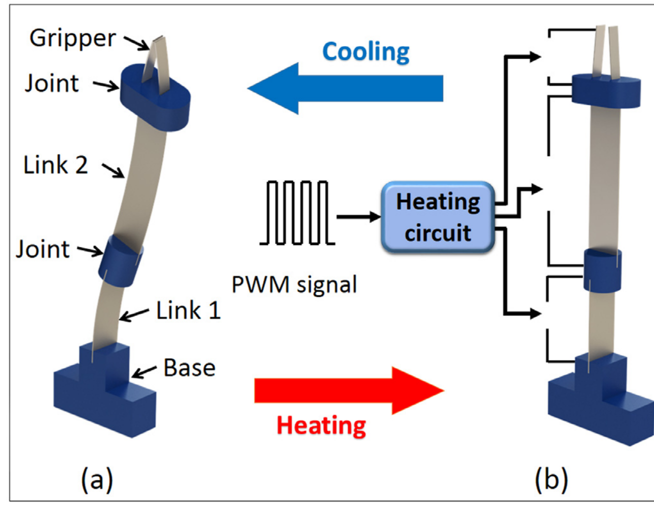


**Fig. 1.** The design of SMA micromanipulator: (a) 3D view of the initial state. (b) 3D view of the fully-actuated state.

**Table 1**
The diminutions of the developed micromanipulator.

| Parts | Width (mm) | Long (mm) | Thickness ($\mu$m) |
|---|---|---|---|
| First link | 3 | 10 | 100 |
| Second link | 3 | 14 | 100 |
| Gripper fingers | 1 | 5 | 100 |
| Overall device | 9 | 33 | $3 \times 10^3$ |

[26]. This method is known as bimorph actuation. Depositing a thin layer of $SiO_2$ as a stress layer at a high temperature onto an SMA sheet surface bends the SMA sheet at low temperatures (martensitic phase) due to the CTE mismatch between the SMA and $SiO_2$, while the SMA sheet returns to a flat form when the temperature increases to an austenitic phase temperature (65 °C in this case). The displacement of the micromanipulator is controlled by adjusting the temperature of the SMA sheet. The actuation of the SMA links can be achieved using the Joule heating principle, which occurs when an electrical current passes through the SMA material. The current flow generates heat in the SMA material, and, consequently, drives the SMA to its austenitic phase [27]. This can be achieved using a heating circuit that generates the PWM signal to control the current flow in the SMA sheet, as shown in Fig. 1(a).

## 3. Theoretical model of the SMA actuators

### 3.1. Thermodynamics analysis of SMA

The temperature of SMA is the major factor in actuation of the SMA sheet. In this paper, the temperature of the SMA sheet is governed by an electric current that is passed through it, resulting in internal heating. Before engaging through the analysis, it is assumed that the only heat loss is due to the convection from the SMA sheet to the surrounding air. The small amount radiation is ignored. During heating, the inner energy of the current passing through the SMA sheet can be expressed as;

$$E_{in} = E_{sma} + E_{siO_2} + E_c + E_{Lh} \quad (1)$$

where $E_{in}, E_{sma}$, $E_{sio_2}$, $E_c$ and $E_{Lh}$ are the inner energy from electrical current, energy of the heat change of the SMA, energy of the heat change of the $SiO_2$ which is deposited above the SMA the convection from the SMA sheet to the surrounding air and latent heat difference resulted from phase transformation, respectively, where