# MEMS Microgripper Actuators and Sensors: The State-of-the-Art Survey

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**Abstract:** In recent years, microelectromechanical systems (MEMS) have been widely applied in diverse science and engineering domains. MEMS-based microgrippers provide advantages in terms of compact size and low cost, and hence play an important role in microassembly and micromanipulation fields for manipulating micromechanical elements, biological cells, etc. During the past two decades, microactuators based on different actuation principles such as shape-memory alloys, electrostatic, electrothermal, piezoelectric, pneumatic and electromagnetic approaches have been devised to drive MEMS microgrippers. Moreover, the integrated position and force sensors can deliver real-time feedback signals to protect both the microgripper and grasped object from damaging. In addition, a number of patents have been devoted to this area. This paper presents a state-of-the-art overview of recent development in the actuators (electrostatic, electrothermal, micro-pneumatic, electromagnetic, shape memory alloy and other actuators) and sensors (optical method, piezoresistive force sensor, capacitive force sensor and other developments). By providing detailed comparisons among them, some guidelines of selection have been underlined for different application scenarios such as biomedical and biological applications, micro-manufacturing and so on.

**Keywords:** Force feedback, force sensor, MEMS, microactuator, microgripper, micromanipulation.

## 1. INTRODUCTION

Microassembly and micromanipulation are widely applied in many fields. In these applications, microgripper acts as a key element for handling fragile objects such as living cells, micromechanical parts, etc. On the other hand, microelectromechanical systems (MEMS) technology allows the development of miniature devices in the order of millimeter, which enables the achievement of compact size, low cost, high resonant frequency, etc. With the increase of interests in microrobotic systems during the past two decades, MEMS-based microgrippers with various types of actuators and sensors have been proposed for the aforementioned applications.

Owing to different properties of actuators, the MEMS microgrippers exhibit diverse performances dedicated to various applications. For example, electrostatic actuation microgripper can provide a large displacement with no hysteresis in a low operating temperature along with a simple structure. Specifically, two different types of movement configuration in terms of lateral comb drive and transverse comb drive can fulfill the objective of high precision and large movement, respectively. In addition, electrothermal actuator can generate a large output force and displacements by making use of its thermal expansion with a small voltage applied. On the other hand, the large force output, precision displacement and rapid response are the attractive points of the piezoelectric actuator. Besides, electromagnetic actuator and pneumatic actuator driven microgrippers can provide a relatively large output force and displacement.

It is known that force sensing is necessary for a delicate micromanipulation task. Nonetheless, before the force-feedback sensor is applied, the optical method has been widely studied. In recent years, researchers showed a great interest in the sensors with high resolution and sensitivity. In order to enhance the reliability and safety of the manipulation, the integrated position and force sensors such as piezoelectric sensor, piezoresistive sensor and capacitive sensor were designed to provide the real-time position and force information. With the advances in the technologies, the sensitivity and resolution of the sensor have been improved substantially. Furthermore, a monolithic design incorporating both actuator and force sensor as shown in Fig. (**1**) is important for inexpensive and simple fabrication and implementation [1].

As a variety of microgrippers have been designed for a wide field of applications, the integrated sensors are also expected to endow the ability of working in different environments. In the following parts of the paper, the reviews of various actuators and sensors used in MEMS microgrippers are presented in Sections 2 and 3, respectively. Section 4 details the performance comparisons of the different actuators and sensors. A conclusion for the current and future developments is summarized in Section 5.

## 2. REVIEW OF THE ACTUATORS

### 2.1. Electrostatic Actuator

Electrostatic actuator has been widely applied in microelectromechanical systems (MEMS). The comb drives are the

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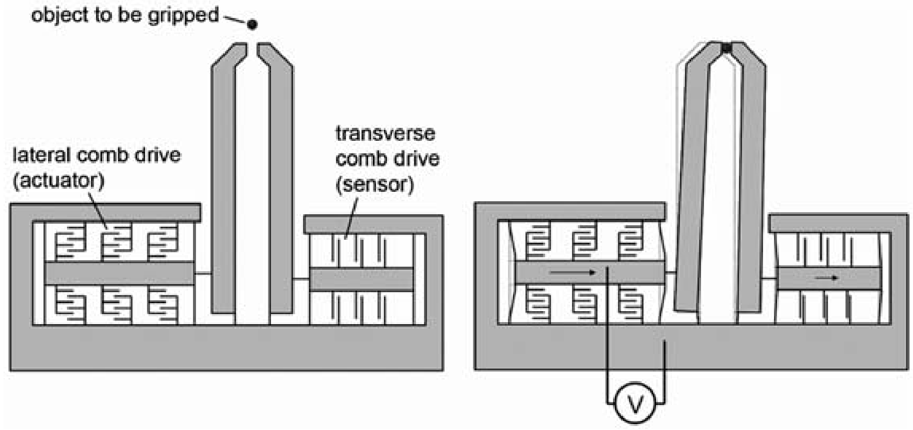


**Fig. (1).** Solid model of the electrostatic microgripper with integrated force sensor [1].

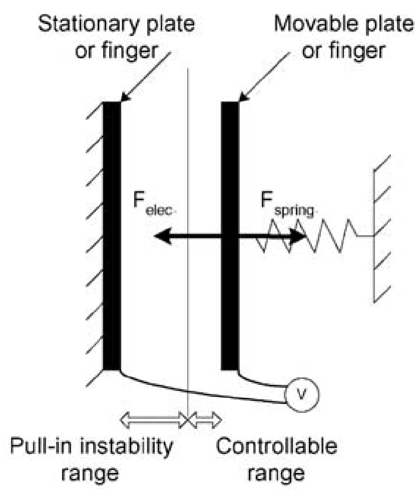


**Fig. (2).** Model of a parallel-plate or transverse comb drive electrostatic microactuator [5].

main components of this type of actuator. The actuator contains a large number of fingers which are parallel-plate capacitors. When the voltage is applied between the movable and fixed plates, the actuator force is generated to move the comb. In the literature, Kim presented a silicon electromechanical microgripper in 1991 [2]. Later, in 1992, the electrostatically driven microgripper was demonstrated to grasp 2.7μm diameter polystyrene spheres, dried red-blood cells and various protozoa in [3].

Since a large gripper opening range is very demanding for a number of applications, many researches have designed flexure structures to enlarge the moving range [1, 4]. Alternatively, increasing the travel range of the comb drive finger is another way. The development of an active control system that stabilizes the actuator and allows travel over almost the entire available gap between comb fingers was presented in [5] as shown in Fig. (**2**). It has been reported that some problems need to be solved, such as the nonlinearity of actuator's dynamics and the variability of system parameters for each device. The authors used a nonlinear model inversion technique and a developed control system based on deep reactive ion etching on silicon-on-insulator wafers.

The electrostatic actuator can be separated into two types, i.e., transverse comb-drive-type and lateral comb-drive-type. It has been shown that the relationship between the finger gap and applied voltage of transverse comb drive electrostatic actuator is nonlinear. The electrostatic force will generate a negative natural spring constant and the mechanical elastic members will also generate a positive spring constant relatively. The distance between the movable and fixed plates is limited by a specific value named "pull-in instability range", and the specific voltage constraint is called "pull-in voltage". If the applied voltage is over this constraint, the fingers will snap in together. As detailed in [5-12], the pull-in instability range constrains the travel distance of elastically suspended parallel-plate and transverse comb drive electrostatic microactuators to approximately 1/3 of the undeflected gap distance. The experiment as conducted by Chan *et al.* showed that the travel range was increased from 0.3μm to 0.6μm out of a 1.0μm total available gap [10]. Nevertheless, the moving range portion of this design was not substantial. Hence, some researchers focused on the charge-controlled [13] and current-controlled method [14]. However, due to the inherent current leakage problem, the actuator's position beyond the pull-in point either cannot be maintained (stable only for a few seconds). Or it can be maintained only by constantly applying refresh current pulses and imposing stringent requirements on current sources' dynamic response [5]. To tackle this issue, it has been reported in [5] that, the moving range of two parallel-plates was increased to 4μm out of 4.5μm full ranges without pull-in effect by using a designed adaptive self-tuning controller. Thus, the actuator travel range portion was improved from near 33% to 80% of the total gap. Detailed control algorithms can be found in the reference [5].

As mentioned before, the electrostatic actuators fall into two different types, i.e., transverse comb-drive-type and lateral comb-drive-type. Concerning the transverse type, due to the nonlinear relationship between the driving force and plates, it is very hard to control near the pull-in point. Considering that the relationship is linear for the lateral type and it is relatively easy to control, the lateral comb-drive-type is preferred to be chosen in the design [15]. This work presented an electrostatically driven microgripper which uses inter-digitated comb drive with non-rectangular finger shapes as shown in Fig. (**3**).

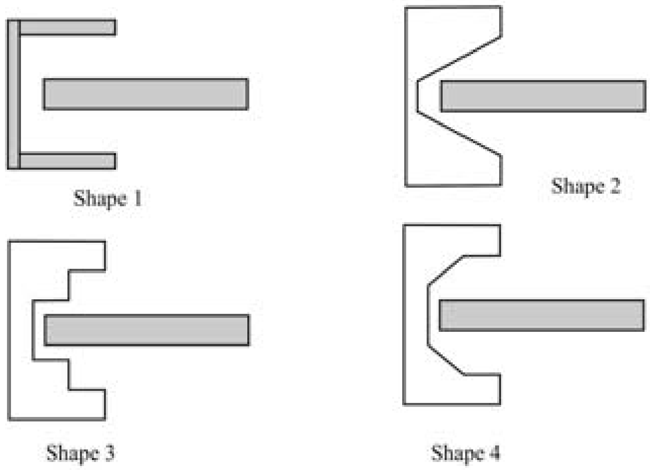


**Fig. (3).** The geometry of electrostatic actuator with proposed finger shapes [15].

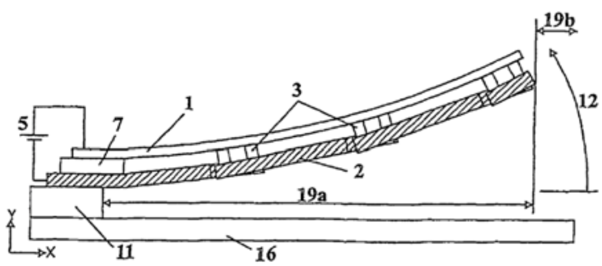


**Fig. (4).** The geometry of proposed finger shapes of the electrostatic actuator [19].

Another issue of the electrostatic actuator driven microgripper lies in that a very high voltage is required to be applied in order to fulfill the large moving range. For instance, the experiments as presented in [15-18] showed that a displacement of 20μm needs an applied voltage of 80 volts with 1020 fingers to actuate, 25μm requires 80 volts with 2904 fingers, and 17μm demands 50 volts with 6400 fingers, respectively. Therefore, in order to discover which one can provide larger displacement with lower voltage and fewer fingers, some different finger shapes have been proposed to test in [15]. Specifically, three different finger shapes (shape 2, shape 3, and shape 4) had been selected and compared with the normal rectangular shape (shape 1). The generated force was calculated by both analytical method and simulation. The conducted experiments showed that the rectangular finger shape model needs a 25-V voltage to move a distance of 6μm. As compared with the other shapes, the minimum voltage was reduced to about 14 V with 28 fingers to produce the same moving range. As a result, the newly designed finger shape can be used to reduce the applied voltage and finger numbers. This indicates an important concept for the further research.

Moreover, a number of inventions have been focused on the electrostatic actuators. For instance, the patent [19] suggested an electrostatic device including a first flexible electrode, on which a plurality of second electrodes are mounted so as to move with the first electrode. When the electrical charge is applied, each second electrode causes deflection of the first electrode whose deflection is enhanced by the movement of the second electrode therewith. As shown in Fig. (**4**), different designs of the device may generate different types of in-plane and out-of-plane movement. In addition, the patent [20] presented an electrostatic actuator with multiple stacked parallel plates as shown in Fig. (**5**). The large confronting area of the charged plates can generate a high magnitude of the force. As a consequence, a large displacement for the stack is produced owing to the cumulative displacement of the individual plates. Besides, a new patent [21] invents an electrostatic actuator which consists of stationary electrodes and movable electrodes. As shown in Fig. (**6**), it enables the use of time-varying voltages with peak values exceeding the pull-in voltage. As a result, it can provide larger electrostatic forces and longer travel ranges with relatively lower applied voltages than typical actuators.

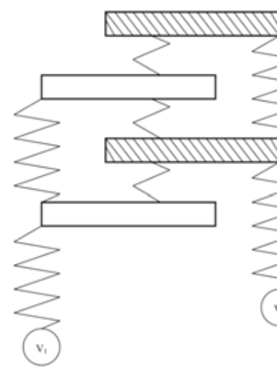

**Fig. (5).** The geometrical of the paralleled plates of the electrostatic actuator [20].

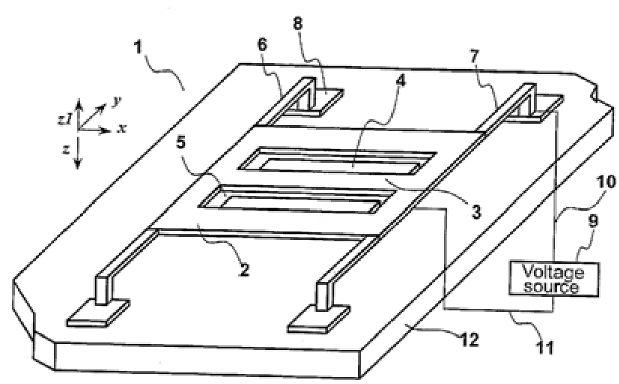


**Fig. (6).** The geometry of proposed electrostatic actuator [21].

## 2.2. Electrothermal Actuator

Electrothermal actuator is also widely applied in MEMS world. Typically, it can generate a large output force by using low voltages. When an electric potential is applied on the conductive material such as metal, the material generates resistive heating and thermal expansion. The structure of actuator is designed so that the direction of thermal expansion can be controlled to achieve desired motions. For example, Fig. (**7**) shows such a design as reported in [22]. It was

**Table 1. The Finite Element Analysis Results [22].**

| Voltage (V) | Displacement (μm) | Maximum temperature (°C) |
|---|---|---|
| 1 | 4.14 | 166.3 |
| 2 | 13.84 | 575.1 |
| 3 | 30.02 | 1256.2 |

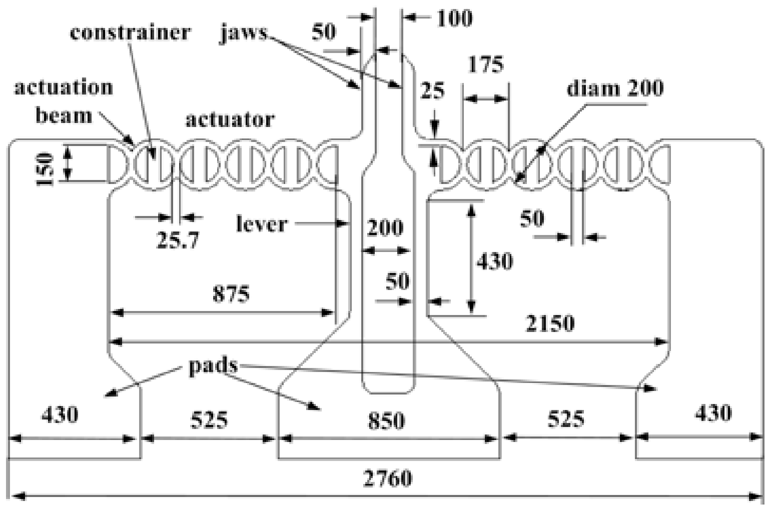


**Fig. (7).** The geometrical design of the electrothermal actuator driven gripper [22].

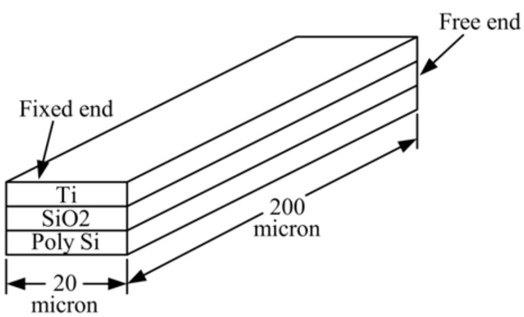


**Fig. (8).** A cantilever of three layers of electrothermal actuator [31].

produced by laser microfabrication technology. The dimension of the entire microgripper was reduced by resorting to the monolithic structure design. In particular, the design employed multi-cascaded structure [23-24] oriented in a face-to-face direction. Five actuation units which are connected in series have been combined as each side of microgripper. In addition, each actuation unit consists of an internal constrainer and two semi-circular-shaped actuation beams. The actuation beam is thinner and has higher electrical resistance than the constrainer. Hence, the thermal expansion of the actuation beam is larger. Since the heated beam tends to expand to all direction, the constrainer is used to restrict the vertical expansion and allow the primary displacements in the desired horizontal direction. The design has been verified by finite element analysis simulations, and the results are shown in Table **1**. The designed structure was fabricated by laser technology along with 5.5% maximum error. The experimental result showed that the maximum displacements were 28.8μm when the voltage of 1.9 V and current of 0.84A were applied.

In addition, many designs based on differential thermal expansion of the multilayer actuator were presented in the literature, e.g., [25-30]. Since micro-cantilever is a basic structure of electrothermal actuator, a three-layer electrothermal MEMS actuator has been designed to generate better performance in terms of deflection and control range of voltage, which also improves the controllability and reliability [31]. As shown in Fig. (**8**), the top, middle, and bottom layers were made of titanium, silicon dioxide, and poly silicon, respectively. The titanium was chosen as the top layer since it offers the largest thermal deflection. A voltage difference is applied across the titanium layer and the surrounding temperature is assumed to be 25°C. Additionally, one end of the structure is fixed, while the other end is left free for deflection. The joule effect is generated when the electrical energy is converted into thermal energy. Consequently, the temperature and thermal expansion increases due to the joule heating effect. It has been shown that, the adjustment of the thickness of different layers results in different controlling range and deflection. In order to achieve a higher reliability, the deflection performance should be reduced as a compromise. When the best overall performance is yielded, the thicknesses of Ti, $SiO_2$, and Poly Si layers are 1, 0.5, and 3μm, respectively.

Besides, owing to the benefits of the SU-8 structure such as high coefficient of thermal expansion (52ppm/°C) [32], relatively large elastic modulus [33, 34], low operating temperature, and high aspect ratio, many SU-8 based electrothermal actuation micrograppers have been designed in the

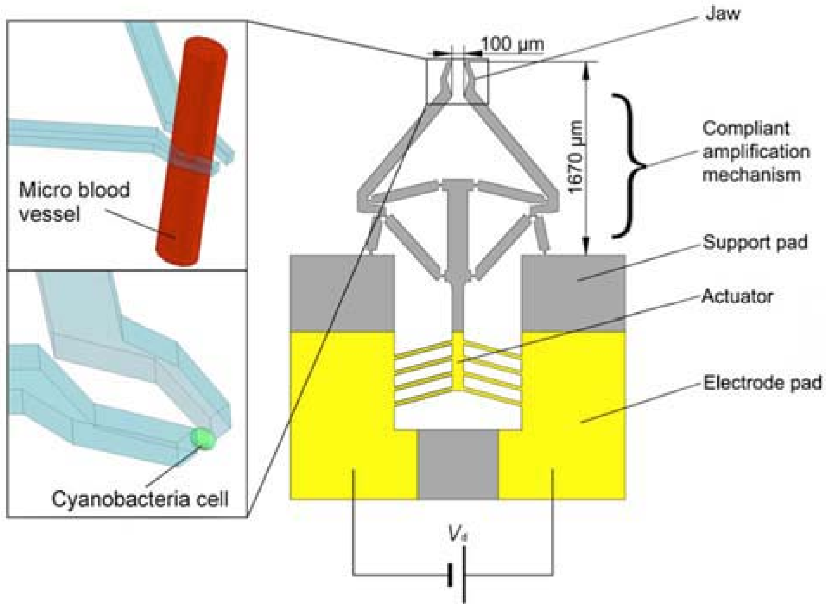


**Fig. (9).** The structure of the microgripper and two gripping modes using different parts of the jaw [36].

literature. For instance, reference [35] presented a microgripper which was inspired by the well-established hot-and-cold-arm actuator design. It is composed of two arms of different widths, which are joined at their free ends to form a U shape. When a voltage is applied, the narrower "hot" arm with higher resistance will generate greater thermal expansion than the "cold" arm. In this design [35], the microgripper consists of a Cr/Au layer which is 67 times thinner than the SU-8 layer. This structure exhibits a high stiffness in vertical direction to avoid the out-of-plane displacement. The experimental results showed that, the average operating temperature changes can be maintained less than 32 $^{o}$C while minimizing thermal loading of the sample by making use of the high coefficient of thermal expansion of SU-8. A displacement of 11µm has been produced with a driving voltage lower than the electrolysis point. Such features enable the proposed actuation mechanism be compatible with liquid operation [35]. Moreover, it has been demonstrated that SU-8 electrothermal microgripper owns good biocompatibility.

As another example, a SU-8 microgripper is shown in Fig. (**9**), which was reported in [36, 37]. It is driven by chevron electrothermal actuator. As compared with the previous hot-and-cold-arm type, this one does not rely on an internal temperature difference to operate. The microgripper was designed by means of type synthesis of kinematic chain. A three-layer sandwich structure (Copper-SU-8-Copper) was adopted to eliminate the out-of-plane displacement. Experimental results revealed that it can obtain a 71.5µm displacement with 195-mV driving voltage and 53.7$^{o}$C temperature changes at the actuator. The response time is about 0.23s during both closing and opening jaws process.

Besides, as compared with other types of electrothermal actuator such as U-beam electrothermal actuators [38-40], V-beam electrothermal actuators require a much smaller chip area and low driving voltage. In addition, they produce larger forces and generate larger displacements by means of amplification [41]. For instance, the microgripper as reported in [41] can generate a range of 65µm with an applied voltage of 10V. Moreover, since the structure of the V-beam electrothermal actuator is easier as compared with other actuators, the microfabrication yield is relatively high.

### 2.3. Micro-pneumatic Actuator

Micro-pneumatic actuator is a type of actuator which employs compressed air as the driving force. This actuator has merits of high energy density, large displacement, large force and usage of various fluids as driving medium which is important for microsurgery manipulation [41]. The basic structure of the actuator contains a piston connected to the housing by two spring elements. When a pressure is applied, the spring elements enable the piston to move and provide the seal against the environment just similar to a bellow piston [41]. The top and bottom parts of the cylinder are made of Pyrex wafers. There is a gap between the Pyrex lids and the sealing structure of some microns to generate the movement of the piston and the spring elements. The experimental results in [41] showed that this structure can provide up to 600µm displacements at about $1.2\times 10^{4}$ Pa pressure.

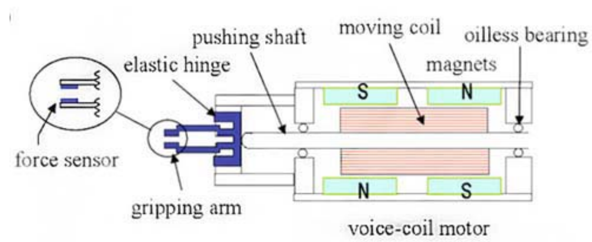


**Fig. (10).** Schematics of the electromagnetic driven micro-gripper design [43].

### 2.4. Electromagnetic Actuator

In recent researches, voice coil motors (VCM) are widely apply to drive precision linear stages [42]. As compared with other actuators, it has a relatively large size and difficult to minimize, there are some advantaged features for microgrippers. For example, it can provide up to several hundreds of microns gripping strokes. The linearization can be more straightforward than piezoelectric actuators, making the robust control of microgrippers possible and the required electronic circuit is simple and cost effective [43]. As shown in Fig. (**10**), the microgripper consists of VCM, elastic hinge, pushing shaft, and gripping arm [43]. The actuator operates with Lorentz forces generated by a current-carrying conductor in a static magnetic field. Applying a voltage to the electromagnetic actuation element leads to linear motion of the pushing shaft. Then, the elastic hinge is deformed to open the gripping jaws. The VCM is operated by a voltage-driven method and the design parameters of the actuator are inextricably coupled to the varying actuating forces. The experimental results in [43] showed that the microgripper can generate a large gripping range up to 300μm with gripping forces up to 18mN.

### 2.5. Shape Memory Alloy

Shape memory alloy (SMA) is an ideal actuator for microgrippers where stroke and energy density rather than speed, is of primarily concern [44]. The shape memory effect as demonstrated by alloys involves a thermally induced crystalline transformation between a ductile phase and a high strength phase [45]. At the low temperature phase (martensitic phase), SMA actuator is easily deformed, and it restores to its original shape at the high temperature phase (austenitic phase). For example, the microgripper as presented in [46] was designed based on this effect. This griper consists of two fingers, a SMA actuator, and a parallel elastic structure providing pull-back force and guiding the movement of the finger. In low temperature phase, the actuator is deformed by the bias spring. When heated, it recovers its original shape to generate the finger displacement. The experimental results demonstrated that the gripper can manipulate the objects of 60-μm width in a congested environment.

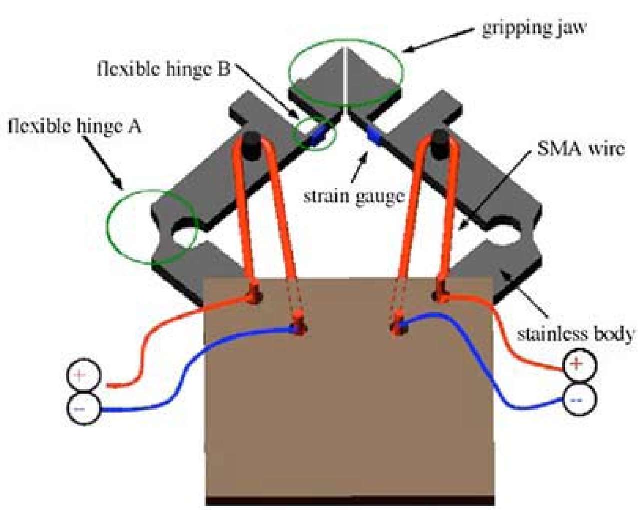


**Fig.(11).** Conceptual drawing of SMA actuated microgripper [47].

In addition, more microgrippers have been designed using SMA wires [44, 47, 48]. For instance, the microgripper as shown in Fig. (**11**) operates as follows. When the SMA wires are energized to generate heat, the wire begins to contract lengthwise at the activating temperature to make gripping jaws displace, and the flexible hinges are designed to generate recovery force when the currents in the two SMA wires are cut off [47].

### 2.6. Other Actuation Methods

Recently, strain structures have been designed to implement out-of-plane movement by the relaxation of a pair of strain-mismatched thin films [49]. This structure can be applied in the field where MEMS must interface with the external environment. When the energy reaches the release point, a single released layer will bend and expand volumetrically elsewhere, resulting in a folded-over flap. However, if the layer is coated with another film having less compressive stress or tensile stress, the upper causing the released bilayer to curl uniformly upward from the substrate [49]. This situation is presented in Fig. (**12**).

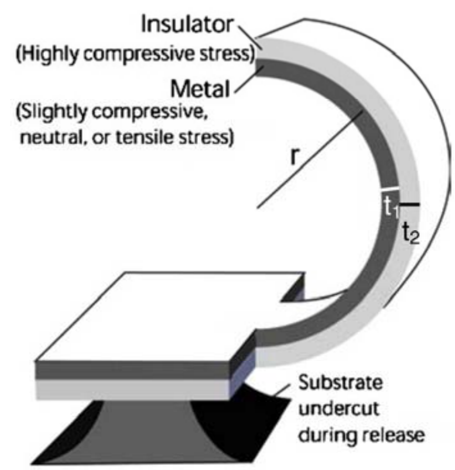


**Fig. (12).** Schematic of a metal-insulator bimorph bending [49].

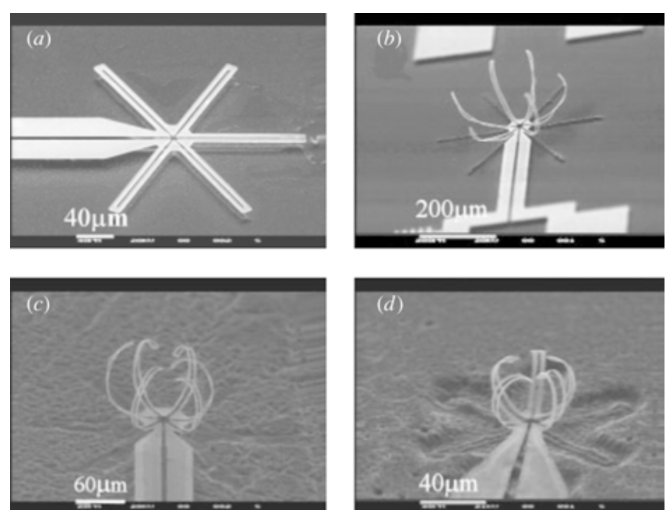


**Fig. (13).** SEM picture of microcage with bimorph structure [50].

A microcage with a bimorph structure of multiple fingers [50] is shown in Fig. (**13**). It has the merit of confining and manipulating micro-objects without applying a force directly to the object so as to avoid the damage. This structure keeps open normally. It requires extremely high temperature and very long fingers to close. The microgripper as presented in [51] also utilized a bimorph layer to form pre-curved fingers. However, the stress is insufficient to form a small fully closed microcage. The typical diameter of long fingers is larger than 500 μm. In order to solve this problem, a diamond-like carbon (DLC) and electroplated Ni bimorph structure based microcage with a radius of curvature around 18μm was designed [50], which is shown in Fig. (**13**). The DLC layer stretches and bends the bimorph layer to form a curved structure. This novel closed microcage is available for grasping micro-objects of sizes 20-50μm. It has been shown that the device can be opened by $90^{o}$ at a power lower than 20mW and operation temperature of $430^{o}$C.

Moreover, the microgrippers fabricated using photolithography were designed [52, 53]. Photolithographic pattering is precise and enables the creation of integrated structures in a highly parallel manner [54-56]. The gripper presented in [52] demonstrated the capabilities of chip-carrying grippers on woven textile fibers and a live caterpillar without any attached wires or electrical power [52]. These wireless structures [57-61] are very important for a variety of applications such as medicine, remote surveillance, etc.

However, when the microgripper is applied in biomedical and biological applications, the application poses some extra requirements in terms of low actuation temperature and low operation voltage, etc. The reason lies in that the gripper with high operated temperature and voltage may damage the living cells, and hence limits its applications

## 3. REVIEW OF THE SENSORS

### 3.1. Optical Method

In order to achieve a precise control of the microgripper, optical method has been developed to visually characterize the movement of microstructures and to provide feedback to control system. An essential part of an effective micro device development is the visualization of the MEMS behaviors, including its motion measurement, profile visualization, and so on [62]. In recent researches, stroboscopic-interferometer system, computer micro vision system, and laser-doppler vibrometer system have been well developed [63]. However, due to its limitation in some MEMS applications, the authors in [62] presented a MEMS measuring system to characterize the dynamics of an actuator, and measure the tip deflection by means of optical focus method.

The microscopic objects can be captured as a digital image of a microscope in optical focusing application [64]. Since the small depth of view may cause blurry image of the motion of the actuator, more reliable method has been developed to solve this problem. Although the continuous stage motion and image acquisition can be used to detect the best focus, only just a few of them can be acquired in the practical case. Therefore, the interpolating method presented in [62] can be used to generate accurate depth estimation. A distinct feature of this method is the depth estimation in the image region, and the displacement of the actuator can be calculated.

### 3.2. Piezoresistive Force Sensor

In practice, force feedback sensor plays an important role during the grasping process. It provides the real-time information of applied force on the object in order to increase reliability. In [65] and [66], electrothermal actuators with piezoresistive force sensors were reported. However, the main limitation of these designs is the relatively large dimensions. On the contrary, the design as reported in [67] presents a novel sensing microgripper as shown in Fig. (**14**).

The gripper is composed of silicon-polymer electrothermal actuators [68] and piezoresistive force-sensing cantilever beams [69]. The silicon comb structure and gripper arm are designed to generate thermal expansion and act as a heat sink in air. When the heat is generated, the thermal expansion bends both the microgripper and piezoresistive sensing cantilever beam. As a result, the resistance of the piezoresistor is changed. The displacement can be monitored by the output voltage of a Wheatstone bridge for the piezoresistive sensing cantilever beam. The contact force between the microgripper jaws and grasped object is then determined from the displacement and stiffness of the microgripper arm [70]. Each actuator owns an aluminum metal heater-based silicon comb finger structure. SU-8 polymer is used to fill the gap of the comber fingers. When the heater is activated, the generated heat is efficiently transferred to the surrounding polymer through the deep silicon comb finger structure that has a large interface area with the polymer layer. The polymer layers expand along the lateral direction and cause a bending displacement of the actuator arm [67]. In the experiments as conducted in [68] and [71], the substrate is assumed to be thermally grounded, and hence, the temperature of the device anchors is fixed, which is equal to the ambient temperature. It has been shown that the heat dissipation into the atmosphere through convection and radiation effects can be ignored in comparison with the heat loss due to conduction in the actuator anchors when the working temperature is below 500K [67, 72-74]. The experimental results showed that the maximum displacement of the microgripper is 32μm and the working temperature is $176^{o}$C at 4.5V. The achieved force sensitivity is up to 1.7nN/m and the corresponding displacement sensitivity is 1.5kV/m.

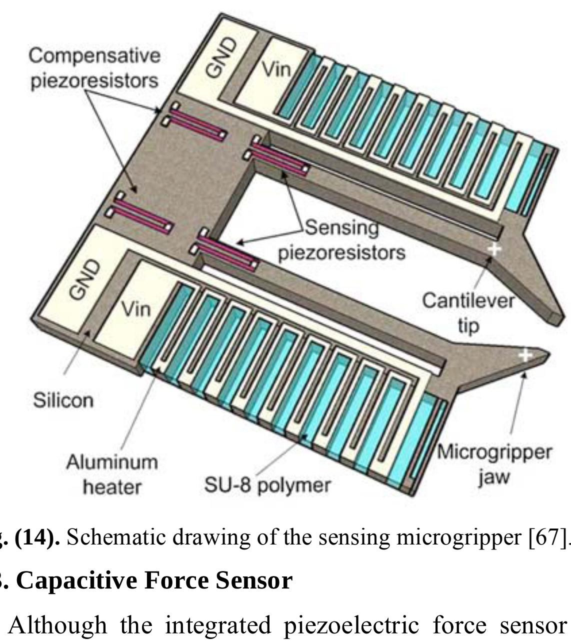


**Fig. (14).** Schematic drawing of the sensing microgripper [67].

### 3.3. Capacitive Force Sensor

Although the integrated piezoelectric force sensor [75] and optical method [76] were developed for force measurement, their major problem lies in the complicated assembly and measurement processes. To overcome this issue, an electrostatic microgripper integrated with a capacitive force sensor has been reported in 2007 [1], which is shown in Fig. (**1**). A monolithic microgripper which combines force sensor and actuator has been devised to reduce the cost and make the fabrication process easier. The fabrication process is based on a process which was originally developed for multi-degree-of-freedom capacitive force sensors [1, 77, 78]. In addition, the actuator employed the lateral comb drives and the capacitive sensor used the transverse comb drive. When a voltage is applied to the actuator, the driving force is generated to move the left gripper arm. After the object is grasped, the gripping force is transferred to the transverse comb drive. The voltage signal is generated by the capacitive readout chip MS3110 from MicroSensors [1, 79]. The gripper opening range is from 0 to 100μm when the applied actuator voltage ranges from 0 to 150V.

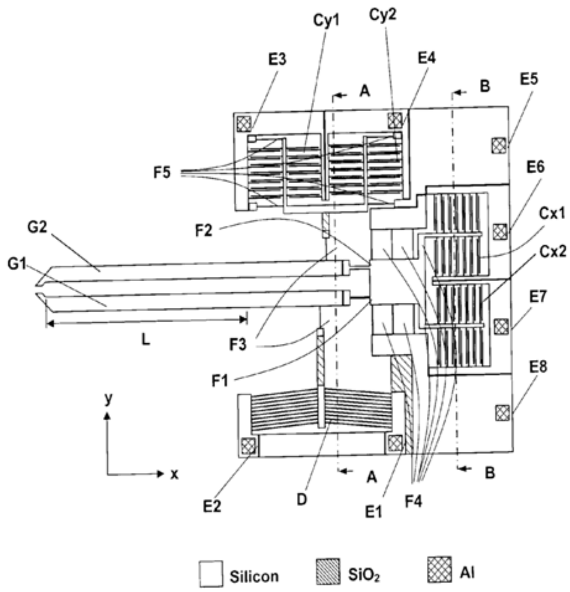


**Fig. (15).** The geometry of microgripper integrated with capacitive force sensor [81].

Besides, the invention [80] described a microgripper and a control system based on a MEMS process. The gripper consists of an electrostatic force sensor, a capacitive force sensor, and two operating arms. The designed control circuit contains three main parts: a force feedback measuring circuit, a driving voltage output circuit, and a central processing unit circuit. The microgripper exhibits the merits of high precision, compactness, and simple structure.

Additionally, a new patent [81] as shown in Fig. (**15**) concerns a design and microfabrication method for microgrippers that are capable of grasping micro- and nanoscale objects of a large range of sizes along with two-axis force sensing capabilities. The integrated force sensor is available for measuring both *x* and *y* directional forces with a high resolution.

### 3.4. Other Development

The patent [82] suggested a calibration method of MEMS sensor. A MEMS sensor can measure an external stimulus and it can be deployed in a particular field environment. However, they typically cannot be calibrated in the field which may degrade the measure accuracy. In order to calibrate the sensor, the sensor is excited and the response is measured in a known environment. For instance, the excitation of the MEMS sensor may be achieved by the processor causing a known voltage to be applied to the electrodes, or a component or device external to the MEMS sensor may apply such a known voltage to the electrodes. In both of the two aforementioned cases, the MEMS sensor is excited electrically.

## 4. DISCUSSION

### 4.1. Comparison Among Actuators

The aforementioned different types of actuators have some merits and drawbacks, which are summarized as follows.

- **Electrostatic actuator**

The electrostatically actuated microgripper can provide a large displacement with no hysteresis in a low operating temperature along with a simple structure. Since the current through the gripper arm is negligible, it can be counted as electrically isolated. The primary limitation of this actuator is its high operation voltage. Many researchers tried to reduce the applied voltage by increasing the number of comb fingers, which may complicate the fabrication process. Besides, the displacement can be increased by designing different shapes of comb finger and extending the travel range of each comb finger without “pull-in” effect.

- **Electrothermal actuator**

The electrothermal actuator can generate a large output force and displacements with a small applied voltage. The fabrication process of this actuator is relatively easy. However, due to its nature of actuation principle, the actuator is heated to provide a thermal expansion. When the microgripper is needed to grasp biomedical objects such as cells in the aqueous environment, the high temperature may be the restriction and some thermal isolation techniques are required for real applications. Another disadvantage lies in its nonlinear expansion when the high operating temperature is induced.

- **Electromagnetic and pneumatic actuators**

The microgrippers based on electromagnetic actuator and pneumatic drive can provide large force output and displacement output. However, large physical size and complicated fabrication processes are their restrictions for the applications in micro and nano scales.

- **Other actuators**

Piezoelectric actuator can generate a large output force and precision displacement. Linear motion and high stiffness are also the characteristics of this type of actuator. The limitations of piezoelectric actuator lie in the small output displacement, expensive fabrication process, and inherent hysteresis effect. Many researchers have proposed flexure structures to magnify the travel ranges.

**Table 2. Performance Comparison Among Various Sensors [1].**

| Fabrication | Force sensing | Sensitivity (mV/μm) | Resolution (nN) | Actuation | Actuation range (μm) | Reference | Gripper length (mm) | Gripper height (mm) | Grasping sample |
|---|---|---|---|---|---|---|---|---|---|
| assembled | piezoresistive | / | 100 | piezoelectric | 213 | [83] | / | / | / |
| assembled | piezoresistive | 1.5 | / | piezoelectric | / | [75] | / | / | / |
| assembled | piezoelectric | 0.0253 | 19000 | magnetic | 300 | [43] | 15.5 | 5.22 | / |
| assembled | none | / | / | pneumatic | 600 | [41] | / | / | / |
| assembled | optical (AFM) | / | 0.016 | piezoelectric | 50 | [76] | / | / | / |
| assembled | piezoresistive | 0.0015 | / | thermal | 32 | [65] | / | / | Micro-glass-ball |
| monolithically | piezoresistive | 0.0001 | / | thermal | 2 | [66] | / | / | / |
| monolithically | none | / | / | electrostatic | 20 | [84] | 1.0 | / | / |
| monolithically | none | / | / | electrostatic | 20 | [85] | 0.5 | / | / |
| monolithically | capacitive | 0.55-4.41 | 70-520 | electrostatic | 100 | [1] | 3.3 | 0.05 | Glass spheres |
| monolithically | none | / | / | thermal | 28.8 | [22] | 2.8 | 1.4 | / |

Besides, SMA actuator can provide a large stroke and energy density with simple driving electronics. The fabrication process is cheap and simple. But, low speed and low energy efficiency are the primarily concerns of this actuator.

### 4.2. Comparison Among Sensors

In addition to the conventional position sensing, real-time force sensing sensor plays an important role in micromanipulation. It can measure the applied force during continuous movement of the microgripper and provides a significant help for grasping fragile objects so as to avoid handling error. Different types of the sensors have been developed such as optical method, piezoresistive force sensor, piezoelectric sensor and capacitive sensor, which are summarized below.

- **Optical method**

Before the force-feedback sensor is applied, the optical method has been widely studied. However, its sensitivity and resolution are relatively low. In addition, due to the reflecting and distorting effect, optical method is not suitable for working in liquid environment.

- **Piezoelectric sensor**

The resolution of the piezoelectric sensor is relatively high. However, the microgripper with integrated piezoelectric sensor requires complicated and expensive fabrication processes.

- **Piezoresistive sensor**

The relatively simple structure design and sensing circuit are the dominant advantages of the piezoresistive sensor. Nevertheless, the piezoresistive sensor can be easily affected by the variation of temperature, size, etc., which may restrict its practical application in some scenarios.

- **Capacitive sensor**

The capacitive sensor can provide high resolution and sensitivity capabilities. The fabrication process is relatively simple and inexpensive. The multi-axis capacitive force feedback as designed in [32] reveals a new trend which can protect the microgripper, detect the contact between the gripper and object, and achieve secured grasping while protecting the grasped object.

Moreover, the comparison of performances of the microgrippers with integrated force feedback sensors and various actuators is summarized in Table **2** for a better understanding of the developments [83-85].

## 5. CURRENT & FUTURE DEVELOPMENTS

During the last two decades, MEMS microgrippers based on various actuation and sensing principles have been developed. Emerging performances have been generated owing to the diverse properties of the actuators dedicated to pertinent applications. In this survey, an overview, classification and comparison of the MEMS microgripper actuators and sensors have been presented.

Because the position/force sensor with high resolution and sensitivity can provide precision and secure reliability during the grasping process, the microgripper with integrated position and force sensors is of most interest in the further research. In particular, the electrostatic actuation microgripper with integrated multi-axis capacitive force sensor demonstrates some advantages [81], i.e., it can deliver a large displacement with a simple structure and accurate position/force feedback control. Furthermore, aiming at the expansion of their applications in various fields, the microgrippers with multi-axis position and force sensors are expected to be designed and developed in the future.

## CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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