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Performance characterization of in-plane electro-thermally driven linear microactuators

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Abstract

Dynamic performance of a microactuator is a key factor in the functioning of an integrated microsystem composed of moving components such as optical shutter, optical switch, micropump, microgripper, microvalve. Therefore, the design of such systems primarily focuses on the overall design and parameter optimization of an actuator as the major driving element with respect to the desired performance parameters, e.g. displacement, force, dimensional constraints, material, actuation principle and method of fabrication. This study presents results on the static (steady state) performance analysis of an in-plane electro-thermally driven linear microactuators. Each microactuator, having a width of $2220\text{ }\mu\text{m}$ and made of $25\text{ }\mu\text{m}$ thick nickel foil, consists of a pair of cascaded structures. Connecting several actuation units in series formed each cascaded structure. A set of microactuators with different number of actuation units was fabricated by the laser micromachining technology. The static performance of these microactuators was evaluated with respect to the maximum linear displacement and applied electric power, current and voltage. The maximum displacements vary from $30\text{ }\mu\text{m}$ to $78\text{ }\mu\text{m}$, respectively, depending on the number of actuation units. The microactuators' performance results are promising for applications in MEMS/MOEMS, microfluidic, and microrobotic devices.

Keywords

microactuator; in-plane motions; electro-thermal actuation; laser fabrication; static performance

1 Introduction

The action-oriented applications of microfluidic, micro-electro-mechanical and micro-opto-electro-mechanical systems (MEMS and MOEMS) such as optical shutters, switches, micropumps, microgrippers, microvalves, require desired performance parameters such as linear/rotary displacements and/or applied forces. These parameters are provided by the static and dynamic performance of a microactuator, which is a key functional element in the design of such systems with moving components. A reliable static performance of the microactuator is crucially required when a high-precision movement and/or precise grasping/holding actions are desired in such microsystems.

Four actuation principles are commonly used for classification of MEMS/MOEMS microactuators: electrostatic, piezoelectric, electro-thermal, and based on shape memory alloy effect [1]. Each microactuator with certain actuation principle has its own advantages and disadvantages, and specific areas of applications. The typical electrostatic microactuators produce relatively small forces ($<10 \mu N$) and displacements ($<5 \mu m$) for applied voltage $> 50 V$ [2]. A larger range of motion and forces are achievable with higher applied voltages [3]. Recently developed electrostatic microactuators with a larger force and motion still require a driving voltage > 100 volts [4]. Piezoelectric actuators also require a higher voltage for generating force and motion, e.g., a voltage of $1000 V$ is necessary to produce $120 \mu m$ deflection [5]. Among the types of actuators mentioned above, electro-thermally driven microactuators are capable of producing longer strokes ($> 100 \mu m$) capable of handling large applied forces ($>1 mN$) with relatively lower applied voltage (typically $< 5 V$) and within smaller design dimensions. Also, they are reliable, easily operated and controllable. Furthermore, electro-thermal actuator is more suitable for microfabrication, handling of miniature parts and objects, assembly operations and in-house packaging.

The first nickel and polysilicon bimorph electro-thermally driven actuators (ETDA) were developed by Guckel *et al* [6] and Comtois *et al* [7]. Other studies and improvements on bimorph ETDA were performed by Huang and Lee [8], and Hickey *et al* [9]. Lai *et al* [10] pointed out that a single typical polysilicon bimorph ETDA can produce a maximum force and displacement of $6 \mu N$ and $6 \mu m$ respectively. Further, an

array of 5 bimorph ETDA's can only provide maximum force of $17\ \mu\text{N}$ while decreasing their total maximum displacement to $3\ \mu\text{m}$. Klaassen *et al* [11] and Williams *et al* [12] have demonstrated an ETDA with a different design configuration referred to as a "V" actuator. Typical forces that can be generated by such "V" actuators are up to several hundred μN [13-15] for a displacement $< 5\ \mu\text{m}$. To obtain larger displacements, motion amplifiers were implemented and attached to "V" actuators [10]. However, the use of motion amplifiers leads to dramatic drop of the output force with respect to the insignificant motion increment. For example, a "V" actuator, comprised of polysilicon beams with $2\times 2\ \mu\text{m}$ in cross section and $200\ \mu\text{m}$ of length, generated a displacement of $3\ \mu\text{m}$ and a force of several hundreds μN . After implementation of a motion amplifier, maximum output force dropped to $3\ \mu\text{N}$ while the maximum displacement increased to $20\ \mu\text{m}$ only [10]. The simulation results of the cascaded "V" shaped EDTAs using polysilicon and nickel reported by Hsu *et al* [16] showed larger displacements, typically $> 100\ \mu\text{m}$ and $250\ \mu\text{m}$ with $10\ \text{V}$ and $0.5\ \text{V}$ respectively. Therefore, the trade-off between output displacement and the force depends on the design, kinematics and material properties of the microactuator.

Recent developments in the microfabrication technologies [1] extend a range of process options for fabrication of miniature functional components and assembly of microsystems from traditional technologies borrowed from the semiconductor industry, including bulk micromachining, wet & dry etching processes, and surface micromachining and LIGA process, to the laser micromachining, focused ion-beam and micro-EDM processes. All these processes have different merits and limitations. For example, the popular MEMS surface micromachining processes, MUMPs (Multi-User-MEMS-Process), is able to produce MEMS devices with two structural layers having a thickness of $2\ \mu\text{m}$ and $1.5\ \mu\text{m}$ respectively [17]. It is well known that such thin structures at a micro scale are sensitive to ambient humidity. The laser micromachining technology is more suitable for rapid prototyping and in some cases for mass production of miniature functional components, microdevices and microsystems with complex 2D/3D geometry having accuracy and precision within $\pm 1\ \mu\text{m}$ from a variety of materials [18-20].

In this article, a set of in-plane, electro-thermally driven microactuators with 2, 4,

6, and 8 identical actuation units linked together forming two parallel cascaded structures, was fabricated from a nickel foil with a thickness of $25\ \mu\text{m}$ using the laser micromachining technology. The static performance of these microactuators is systematically characterized with respect to the maximum linear displacement and applied electric power, current and voltage.

2 Microactuator design

Figure 1 shows the detailed design of the microactuator, a single actuation unit and fabricated microactuator prototype with two cascaded structures with eight actuation units in each structure. The dimensions of all the design elements are listed in Table 1. The actuator design is based on a multi-cascaded approach [16, 19, 21]. It consists of a pair of identical, in-plane, cascaded actuation structures linked together at the top by a horizontal motion platform. Each cascaded structure is formed by a serial connection of several basic actuation units magnifying the output in-plane displacements. A driving electric potential was applied between the two fixed electric pads (anchor 1 and 2) at the bottom of each cascaded structure. The actuation principle is based on the electro-thermal effect. When the electric current runs through the conductive structure of the microactuator it produces Joule heating, generating thermal expansion of all the elements and eventually the entire solid structure. As a result of the thermal expansion of all actuation units in cascaded structures, the motion platform moves forward producing output in-plane displacements and force. The symmetric monolithic structure was chosen to provide a symmetrical distribution of the voltage, temperature and displacements along each vertical cascaded structure and the entire actuator. More detailed description of the design of similar microactuators can be found in Ref. [19]. It is important to note that the design of the microactuator allows optimization of the structural aspects with respect to the desired displacements by selecting a certain number of actuation units and with respect to the desired force by choosing a number of the cascaded actuation structures.

Each actuation unit consists of two pairs of mirrored “V” beams, called actuation beams, joined together at the inner ends as shown in Figure 1b. The outer ends of the actuation beams are attached to a wider bar called constrainer referring to its functional

purpose, described below. A design combination of two “V” actuation beams and a constrainer is similar to a cascaded open toggle mechanism [10] with a difference that outer actuation beams are fixed to a substrate. Since the dimensions of the thin, long actuation beams are $10\ \mu\text{m} \times 25\ \mu\text{m}$ (width to thickness) in cross-section, they have a higher electrical resistance compared to the wider constrainer with a cross-section of $30\ \mu\text{m} \times 25\ \mu\text{m}$. Figure 2 shows an electric equivalent to the actuation unit as a Wheatstone bridge formed by the resistances of four actuation beams, R_1 to R_4 , and the constrainer (R_5). The four actuation beams, R_1 to R_4 , have equivalent resistances (R_1 to R_4) by design, and consequently, the bridge is always balanced. In the balanced Wheatstone bridge, no electrical current flows through the diagonal resistance, R_5 , represented by the constrainer. In the fabricated prototypes, it was observed that the Wheatstone bridge was working under a well-balanced status with negligible current leakage through the constrainer. Therefore, under the Joule heating conditions, only the actuation beams, R_1 to R_4 , were expanded pushing forward the rest of the actuation units with respect to the fixed anchors. The Joule heat generated in the constrainer, R_5 , was insignificant. The only source of thermal expansion of the constrainer is the heat transferred from the actuation beams. As a result, the actuation beam expands significantly more than the constrainer during the electro-thermal heating stage. In addition, when the actuation unit is electrically heated, actuation beam tends to expand in all directions evenly and the constrainer limits the expansion of the actuation unit in the horizontal direction. Consequently, the constrainer directs the primary displacements towards the desired vertical direction. When electrical potential was applied between the two anchors, the output displacement was generated from the summation of the responses of all the basic actuation units in one cascaded structure. The directions of motion can be outward (stretching mode) or inward (shrinking mode), depending on whether the actuation beams were under expansion or contraction.

A set of microactuators with a different number of actuation units, in particular, 2, 4, 6 and 8, were fabricated from a $25\ \mu\text{m}$ thick nickel foil using the laser microfabrication technology. The parameters of the laser-material removal process, such as laser power, pulse repetition rate, working distance, and feed rate, were optimized in order to achieve accuracy and precision of the fabricated prototype within $\pm 1\ \mu\text{m}$. More

detailed information on the laser micromachining system and fabrication challenges can be found in Refs. [18, 19, 21].

All ETDAAs utilize the principle of thermal expansion resulting from Joule heating caused by the electric current flowing through the solid body of the actuator made of electro-conductive material. However in practice, a direct length increment available from the thermal expansion of a heated actuation beam is too small to be used as an actuation motion in functional microdevices. For example, a beam of the dimensions 200(L)x10(W)x25(T) μm , made from commercial pure nickel with a coefficient of linear thermal expansion of $\alpha = 8.5\sim 14.0 \times 10^{-6} \text{ 1/K}$ [22] heated up from 20 °C to 100 °C, expands approximately 0.14~0.22 μm . Therefore, the electro-thermally driven microactuators normally require design elements and structures to further amplify these small motions.

3 Kinematic analysis of an actuation unit

Figure 3 shows two conceptual kinematic models of an actuation unit, where an actuation beam with one degree of freedom (linear extension) can be kinematically modeled as two undeformed links with one prismatic joint. The outer end of each link has a rotary joint providing one degree connection (rotation around the joint) with the constrainer and mirrored actuation beam. The constrainer has a constant length and provides a geometrical constraint acting as a frame preventing transverse motions. Each half of the actuation unit can be modeled as a planar five bar mechanism (Figure 3a), or each quarter of the actuation unit can be modeled as a four bar mechanism (Figure 3b). The input motions, i.e., small thermal expansions of actuation beams, are converted into larger output in-plane linear motions by the design and kinematics of the actuation unit. The magnification depends on the actuation angle β , between the actuation beam and the constrainer. For smaller angles, the magnification can be approximated by [9,10]:

$$\frac{1}{\tan \beta} \quad (1)$$

Thus, decreasing the angle β increases the achievable magnification. For example, for $\beta=6^\circ$, the approximate magnification is 10 times; for $\beta=3^\circ$, the magnification

is 20 times. The analysis results agree with the simulation results reported in Ref. [16].

The total output displacement is the accumulation of the resultant output motion of every single actuation unit and one cascaded actuation unit delivers the same amount of force as that generated by a single actuation unit. Further, the actuator, formed by two parallel identical cascaded actuation units, would double the output force. To obtain even larger output force, increasing the number of the actuation beams in each actuation unit could be a preferred choice.

4 Performance evaluation setup and procedures

Figure 4 shows an experimental setup for the performance evaluation of the prototype microactuators. It consists of a power supply (XANTREX, HPD 15H20), normally open push button, digital oscilloscope (LeCroy WaveRunner, LT354), desktop computer and optical microscope (Olympus, SZX12) with a CCD camera under Visual GaugeTM software control. The microactuator was mounted on a small piece of epoxy circuit board glued to a plastic container and was wired to a standard socket as shown in Figure 5. The geometrical resistance values R_1 to R_4 were calculated to be $0.15\ \Omega$, and R_5 is $0.1\ \Omega$, that resulted in an electric resistance of $0.15\ \Omega$ for the each actuation unit. The measured electric resistance of each microactuator with a number of actuation units, 2, 4, 6, and 8, was $1.2\ \Omega$, $2.0\ \Omega$, $3.0\ \Omega$ and $3.6\ \Omega$, respectively. An average resistance increment for every two pairs of actuation units was $0.8\ \Omega$, and hence, the resistance of each actuation unit was estimated to be of $0.2\ \Omega$. The microactuator was connected to the oscilloscope from the socket to BNC by an adaptor wire with electrical resistance of $0.6\ \Omega$.

The performance evaluation involved the following steps. By pushing the button, a driving voltage as a step input from the power supply was applied to the microactuator, simultaneously, the driving voltage was recorded by the digital oscilloscope, and the in-plane output motions were captured by a CCD camera through the optical microscope for further analysis. Figure 6 shows a typical dynamic response and setting of the prototype microactuator under the step voltage input. It takes approximately 1 second for the microactuator to reach the steady state that characterizes the static performance of the microactuator. The output displacements with respect to the applied voltage and

current were measured when the microactuator had reached its steady state.

Thermal microactuators fabricated by silicon micromachining process typically exhibit electrical resistances of the order of several $k\Omega$ [9, 10] with a resistance of connection wires $< 1 \Omega$. Therefore it can be assumed that all the applied voltage was used up in testing the microactuator. For metal-based microactuators with a solid structure presented here, the actuators have resistance values of only a few Ohms, which is of the same order as that of the connection wires. A driving electric current and power were selected as measurable input parameters for evaluation of the actuators' static performance. This study is focused on characterization of the static performance only, i.e., after the microactuator has reached its steady state follow the application of the electric current. The dynamic performance of the microactuator that can be characterized by an impulse response function, natural frequencies, modes and other dynamic characteristics, is outside the scope of this paper.

5 Results and Analysis

5.1. Maximum output displacement

Figure 7 shows the output displacements versus applied current for microactuators with different number of actuation units. It shows that the microactuators with 2, 4, 6 and 8 actuation units reach their maximum output displacement of $33 \mu m$, $44 \mu m$, $64 \mu m$ and $78 \mu m$ at current level of 0.60 A, 0.46 A, 0.47 A and 0.49 A respectively.

5.2. Buckling effect

For the current above the values indicated in Sec. 5.1, the actuators started to buckle and their output displacements dropped dramatically. Figure 8 shows an example of buckled actuation beams with buckling offsets of $6 \mu m$ and $9 \mu m$ from the original positions. The buckling effect could be explained as follows. All actuation beams are slender under longitudinal axial compression loads. These may include internal deformation loads, external loads or their combination. With the continuous increase in the applied current, the actuation beam continuously generates larger thermal expansion and therefore, output motion is directed against the increasing internal (from thermal expansion) and/or external (from interconnected actuation units) axial loads. Once the axial load exceeds a critical value, the beam becomes elastically

unstable [23] and buckling occurs causing permanent deformations within the original geometry of the actuation beam, as shown in Figure 8. These deformations reduce the output force and displacement values, and may cause eventual failure of the actuator. The electric current and power, under which a microactuator turns into elastically unstable structure and loses its desired performance, is referred here as the buckling current and power. In this paper, the buckling effect was analyzed for the actuators with 2 and 6 actuation units only. The microactuators with 4 and 8 actuation units reached their maximum displacements with currents very close to the individual buckling current values. The buckling current for microactuator with two actuation units was 0.6 A, a value higher than the microactuator with six actuation units (0.47 A), because of the larger external axial loads generated and also inter-effected by all six actuation units.

5.3. Efficiency of the actuation units

In order to determine the effect of changing number of the actuation units, a normalized output displacement was calculated for each microactuator by dividing measured displacements by the number of actuation units. Figure 9 shows the normalized output displacements. This normalizing procedure allows an estimation and analysis of the efficiency of the actuation unit in terms of the output displacement with respect to the applied current. Figure 9 demonstrates the linear performance with average efficiency of 10 $\mu\text{m}/\text{A}$ per actuation unit below 0.35 A. The performance per actuation unit of all microactuators significantly increases above 0.35 A, e.g., the microactuator with two actuation units has maximum efficiency per actuation unit of 30 $\mu\text{m}/\text{A}$ and generates four times longer displacements of 16.5 μm with 0.6 A compared to 4.0 μm with 0.35 A.

5.4. Electric power consumption

Figure 10 shows the output displacements versus the input power and provides a comprehensive analysis of the electric power consumption by each microactuator. It was observed that the actuators start buckling as the input power is increased beyond 0.4 W. For input power below 0.4 W, the output displacements were linearly proportional to the driving power. Results presented in Figure 10 indicate that the output displacements are not proportional to the numbers of actuation units. For applied power below the bulking value, the lesser the number of actuation units, the larger the output

motion each actuation unit can generate, e.g., for 0.2 W applied power, the total displacements of 12 μm , 16 μm , 18 μm , 16 μm were generated by the microactuators with 2, 4, 6, and 8 actuation units, and the corresponding displacements per actuation unit were 6 μm , 4 μm , 3 μm , and 2 μm , respectively. For a certain input power, the microactuator with less actuation units has less electric resistance and experience higher current for each actuation unit. Consequently, more Joule heating and larger thermal expansion were produced resulting in larger output displacement per actuation unit. The results on the power consumption per actuation unit are presented in Figure 11 as the normalized output displacements with respect to applied power per actuation unit. This data also shows that the buckling power per actuation unit decreases as the number of the actuation units increase, e.g., 0.21 W and 0.11 W of power were required for buckling of the microactuators with 2 and 6 actuation units, respectively. This phenomenon can be explained by a cross-influence between the dynamic performances of the entire microactuator and the actuation unit. Due to the cascaded structure design, each actuation unit generates forward and backward motions under thermal expansion and cooling contraction, respectively. During actual functioning, the backward motions create compression loads for the previously linked actuation units and each load is compensated by a structural stiffness of the entire microactuator. The microactuator with more actuation units has less structural stiffness, and therefore, less buckling power/current was required.

6 Comparison with other observations

For benchmarking purpose, the microactuator with 4 actuation units was compared with the Ni-based actuators presented in Refs. [15] and [16] in terms of maximum output displacements and power consumption with respect to the geometric dimensions. Also, the sub-basic unit of the microactuators was defined as a chevron shape formed by two single actuation beams. Thus, a basic actuation unit of the microactuators in Ref. [16] and in the present article has two sub-basic actuation units. Table 2 lists compared characteristics.

It was shown in Sec. 3, that the output displacement increases as the actuation angle β decreases. As expected, the microactuator in Ref. [16] generates the largest

output motion because of its sharply oriented beam angle of 1° . The critical load of a slender beam P_{cr} is given by [23]

$$P_{cr} = \frac{\pi^2 EI}{L_e^2} \quad (2)$$

where E is the modulus of elasticity, I is the moment of inertia of the cross-section with respect to the buckling-bending axis; L_e denotes the equivalent length of a column. The microactuators studied in this paper, have a higher value of I due to a larger cross-sectional area. Therefore, they can carry a larger compression load and provide better in-plane performance such as anti-buckling and free from out-of-plane bending. Also, the larger cross-sectional area enables significantly larger force, e.g., the microactuator with four actuation units produced approximately $2600 \mu N$ force with a driving current of $0.4 A$.

7 Summary and Conclusions

In the present article, a systematic study of the static performance of the in-plane electro-thermally driven linear microactuators is presented. A set of microactuators with different number of actuation units, in particular, 2, 4, 6 and 8, were fabricated from a nickel foil with a thickness of $25 \mu m$, and accuracy and precision within $\pm 1 \mu m$ using the high-precision laser microfabrication technology. The static performance of the prototype microactuators was analyzed with respect to the maximum output displacements, electric power consumption and functional efficiency. The maximum in-plane displacements of $33 \mu m$, $44 \mu m$, $64 \mu m$ and $78 \mu m$ were achieved with the currents of $0.60 A$, $0.46 A$, $0.47 A$ and $0.49 A$, respectively.

The following conclusions can be drawn from these studies:

1. The analyzed microactuator is a highly efficient miniature mechanism capable of generating output displacements reliably and of the order of at least 10% of its linear dimension with minimal power consumption of $0.42 W$.
2. The high-actuation performance of the each actuation unit is a result of an innovative combination of the rhombus-shaped design and the electric equivalent of Wheatstone bridge formed by the resistance values of the four actuation beams.

3. The efficiency of the microactuators depends upon on the number of actuation units in each cascaded structure. In general, an actuator with more actuation units produces larger output displacements, but this functional relationship is non-linearly proportional the number of actuation units.
4. The efficiency of the single actuation unit is a function of a number of such actuation units in the design of the cascaded structure. The output displacement and the electric power consumption per actuation unit increase as the number of actuation units decreases.
5. The reliable static performance of each microactuator is limited by the buckling of the actuation beams when the compression load exceeds the thermal expansion force. The buckling effect depends on the number of the actuation units and driving current/power. The range of the buckle-free operation increases with an increase in the number of actuation units.

The presented results strengthen the usefulness of the prototype microactuators for applications in MEMS/MOEMS, microfluidic, and microrobotic devices.

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Dimensions of the design elements

Table 1.

L	1000	C1	60
W	10	C2	30
β	5°	C3	30
D	30	C4	$L+2*S+C2+Cd$
S	30	P	500
MC	30	Cd	100

Note: 1. All dimensions in μm , except β , which is in degree
 2. Anchor 1 and anchor 2 are electrical contact pads.

Comparison of selected nickel-based microactuators			Table 2.		
			selected Ni-based Microactuators for comparison		
parameters			reference [15]	reference [16]	this paper
number of actuation units			1	10	8
dimensions of the actuation beams	width (μm)		8	6	10
	height (μm)		11	3	25
	length (μm)		1000	410	1000
	actuation angle, (degree)		1°	2.89°	5°
max displacement (μm)			10	200	44
max displacement per actuation unit (μm)			10	20	5.5
max input power per actuation unit (mW)			140	66*	53
resistance of the entire actuator (Ω)			5.5	13.7*	2
method of fabrication			electroplate	electroplate	laser

Note: * These are approximations that were calculated.

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Figure 1. Detailed design and fabricated prototype of a microactuator with eight actuation units.

Figure 2. Electrical Wheatstone bridge of an actuation unit.

(a) five-bar mechanism

(b) four-bar mechanism

Figure 3. Kinematics of an actuation unit.

Figure 4. Experimental setup for performance evaluation.

Figure 5. A mounted microactuator with connection wires.

Figure 6. Typical dynamic response and setting of a microactuator.

Figure 7. Output displacements with respect to the input applied current.

Figure 8. Example of buckled actuation beams.

Figure 9. Displacements per actuation unit with respect to the applied current.

Figure 10. Output displacement with respect to the applied power.

Figure 11. Displacements per actuation unit with respect to the power per actuation unit.