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# Modelling and experimental analysis of a U-shaped electro-thermal actuator

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**Abstract.** Electrothermal micro-actuators have gained significant attention over the past two decades due to their unique method of movement that leverages electricity to generate heat. This electrothermal approach has several advantages compared to other actuation mechanisms like electrostatic or piezoelectric effects. Notably, it allows for flexibility in material selection, cost-effective fabrication, and substantial displacement capabilities. The paper presents the analytical, numerical and experimental study of U-shaped arm actuator. To validate the analysis methodology the actuator was designed at macroscale level in two configurations, one made of aluminium and one with two different materials for hot and cold arms. The first variant was analytically and numerically analysed under electrothermal actuation. The second variant made of plastic and aluminium arms was heated up by hot air under temperature monitoring with a thermal camera. The displacements of the structure were measured by the optical method of Digital Image Correlation. Finite element models were created to get the displacements of the actuator under external temperature or by electrothermal actuation. The proposed methodology was validated, and the influence of different geometrical parameters was investigated.

**Keywords:** electrothermal actuators, modelling, digital image correlation

## 1. Introduction

U-shaped electro-thermal actuators, also known as hot-and-cold arm actuators, have become an important technology in the field of micro-electromechanical systems (MEMS) due to their efficient conversion of thermal energy into mechanical displacement. These actuators utilize differential thermal expansion to produce movement, making them suitable for applications requiring substantial displacement and force. This paragraph provides a comprehensive overview of the design principles, material selection, analytical and numerical modelling, experimental

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validation, and applications of U-shaped electro-thermal actuators, with a focus on recent advancements and research.

The fundamental design of U-shaped electro-thermal actuators involves two arms: a hot arm, which heats up and expands significantly, and a cold arm, which either remains at a lower temperature or has a lower thermal expansion coefficient. The differential expansion between the two arms creates a bending motion, resulting in mechanical displacement. The key parameters influencing the performance of these actuators include the material properties, geometric dimensions, and the method of heating.

Material selection is crucial for optimizing the performance of U-shaped electro-thermal actuators. Common materials include silicon, polysilicon, aluminum, and various composites. The choice of materials affects the thermal conductivity, expansion coefficients, and mechanical strength of the actuators. Aluminum is commonly used due to its high thermal conductivity and favourable mechanical properties. Recent studies have explored the use of advanced materials such as silicon carbide (SiC) and titanium alloys. SiC, for instance, offers excellent thermal stability and mechanical strength, making it suitable for high-temperature applications (Kaur et al., 2021). Titanium alloys, on the other hand, provide a good balance between thermal expansion and mechanical properties, which can enhance actuator performance in specific scenarios (Jiang et al., 2022).

Analytical and numerical models are essential for predicting the behavior of U-shaped electro-thermal actuators. These models help in understanding the thermal distribution, mechanical deformation, and overall performance of the actuators under different operating conditions. Analytical models typically involve solving the heat transfer equations and the equations of motion for the actuator. These models provide insights into the temperature distribution and the resulting displacements. Early analytical models by Guckel et al. (1992) laid the groundwork for understanding the thermal and mechanical interactions in these actuators. More recent models have incorporated complex factors such as non-uniform heating and material anisotropy (Wang et al., 2020). Numerical methods, particularly finite element analysis (FEA), have been widely used to simulate the performance of U-shaped electro-thermal actuators. FEA allows for detailed modelling of the thermal and mechanical responses of the actuators, including the effects of various geometrical parameters and material properties. Recent advancements in FEA have enabled the simulation of more complex actuator designs and operating conditions. For example, Chen et al. (2021) used FEA to study the impact of varying arm lengths and cross-sectional areas on actuator performance, providing guidelines for optimizing actuator design. Additionally, multi-physics simulations that couple thermal, electrical, and mechanical effects have become more prevalent, offering a more comprehensive understanding of actuator behaviour (Zhou et al., 2022).

Experimental validation is critical for verifying the predictions of analytical and numerical models. Techniques such as Digital Image Correlation (DIC) and thermal imaging are commonly used to measure the displacement and temperature distribution of U-shaped electro-thermal actuators. DIC is a non-contact optical method that captures high-resolution images of the actuator before and after heating.

By comparing these images, precise measurements of surface displacements can be obtained. Chu et al. (2011) demonstrated the effectiveness of DIC in capturing detailed deformation patterns of electro-thermal actuators, providing valuable data for model validation. Thermal imaging is used to monitor the temperature distribution across the actuator in real-time. This technique helps in identifying thermal hotspots and assessing the efficiency of heat transfer within the actuator. Li and Que (2002) utilized thermal imaging to study the thermal efficiency of bimorph electro-thermal actuators, highlighting areas for potential improvement.

U-shaped electro-thermal actuators are used in a variety of applications due to their high displacement capabilities and relatively simple design. Key application areas include optical systems, micro-robotics, biomedical devices, and precision positioning systems.

Electrothermal actuators have been extensively researched for applications in Micro-Electro-Mechanical Systems (MEMS). Their primary use is in the field of micro- and nano-manipulation, where they serve as essential components in tools like microgrippers and micro positioners. These instruments are critical for tasks such as micro-assembly, biological cell manipulation, and material characterization. Additionally, recent applications have expanded to include switching and latching mechanisms, demonstrating the versatility and utility of hot-and-cold-arm actuators in various advanced technological fields. In optical systems, U-shaped electro-thermal actuators are used for precise alignment and adjustment of optical components. Reza et al. (2015) developed an actuator for optical alignment, achieving high accuracy and repeatability. In micro-robotics, these actuators provide the necessary force and displacement for manipulating small objects or performing intricate tasks. Li et al. (2018) designed a micro-robotic system using U-shaped actuators for minimally invasive surgical procedures, showcasing the potential of these actuators in advanced medical applications. In biomedical devices, U-shaped electro-thermal actuators are used for applications such as drug delivery systems and micro-surgical tools. Their precise control and small size make them ideal for these applications. Recent studies have explored the use of biocompatible materials to further enhance the suitability of these actuators for biomedical applications (Kim et al., 2020).

## 2. Materials and methods

This study focuses on the analytical, numerical, and experimental examination of U-shaped arm actuators. The investigation was conducted using two macro-scale configurations of the actuators. The first configuration was made entirely of aluminium, while the second configuration utilized two different materials for the hot and cold arms, specifically aluminium and plastic (Ultrat).

### 2.1 Analytical model

The macro-scale model U-shaped actuator was designed using Solidworks software and its dimension of the is presented in Fig. 1.

An analytical expression was derived by Hickey et al. in [12] based on energy methods to calculate displacements including the axial and bending energy of the system.

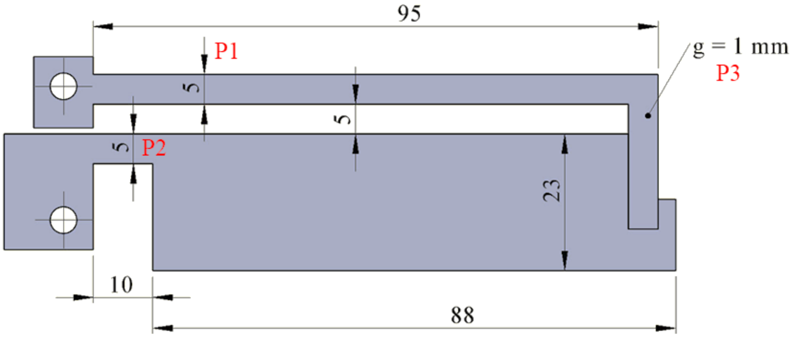


Fig. 1. Geometrical model of the U-shaped hot-and-cold-arm actuator.

For simplification few assumptions were proposed: a) The cold arm is stiff, therefore, its expansion and bending are neglected, and b) the hot arm and the flexure zone of the cold arm have identical cross-section area, *A*, and moment of inertia, *I*. The lateral deflection of the tip of a standard U-shape actuator can be expressed as follows [12, 13]:

$$\delta_x = \frac{1}{2} * \frac{(a^4 - a^2 + 2a) A r \propto \Delta T L^2}{5a^4 I + a^4 r^2 A - 2a^3 I + 5aI + r^2 aA + I + a^5 I - 2a^2 I} \quad (1)$$

where α is the coefficient of thermal expansion, $\Delta T$ is the net temperature difference, *L* is the length of the actuator, *a* is the ratio of the flexure length *l* to the hot arm length, *r* is the centre to centre spacing between the hot arm and the flexure and *A* and *I* are the cross-section area and the moment of inertia of the hot arm (flexure) respectively.

Geometrical parameters presented in Table 1 were used to calculate the deflection of the actuator based on above formula, the resulting value being $\delta_x$=0.651 mm.

Table 1. Geometrical parameters of the actuator

| *L* (mm) | *l* (mm) | *a* | *A* (mm$^2$) | *I* (mm$^4$) | *r* (mm) | Α (1/°C) | Δ*T* (°C) |
|---|---|---|---|---|---|---|---|
| 95 | 10 | 0,105263 | 15 | 31,25 | 10 | 0,000023 | 43 |

## 2.2. Numerical model

Finite element models were developed in ANSYS Workbench to simulate the displacements of the actuators under both external temperature changes and electrothermal actuation. The geometrical models were meshed with thetraedral elements with an element length of 8 mm. The boundary condition consists of fixed support attached to the fixation holes and a uniform temperature change in the case of U-shape actuator build by two different materials and electrothermal actuation for a variant having homogeneous material.

The variant build by two materials consists of an aluminium “hot arm” and a plastic material realized by 3D printing (Z-Ultrat produced by Zortrax) for the “cold arm”. The materials have different coefficients of thermal expansion, 23E-05 (1/°C) for aluminium and 8.82E-05 (1/°C) for Z-Ultrat, due to this difference by heating up the actuator from room temperature of 20°C to 70°C the bending effect and the corresponding displacements occurs as presented in Fig. 2.

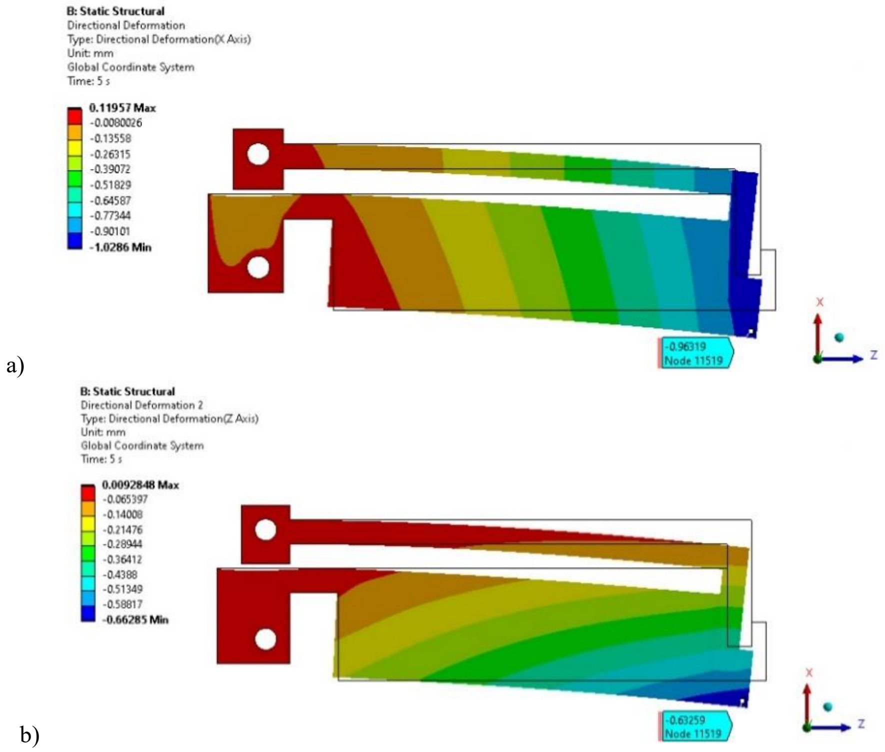


Fig. 2. In-plane actuator’s deflection ($\Delta T=50°C$): a) along X axis, b) along Z axis.

The maximum directional deflections corresponding to a thermal change of 50°C were recorded at the tip of the U-shape actuator and has the value $\delta_X=1.028$ mm and $\delta_Z=0.662$ mm

Electro-thermal analysis was realized by an actuator made of aluminium under a voltage of 50mV, air convection (stagnant air with a film coefficient of 5E-006 $W/mm^2\cdot°C$) and having the same clamping conditions in the holes area (Fig. 3).

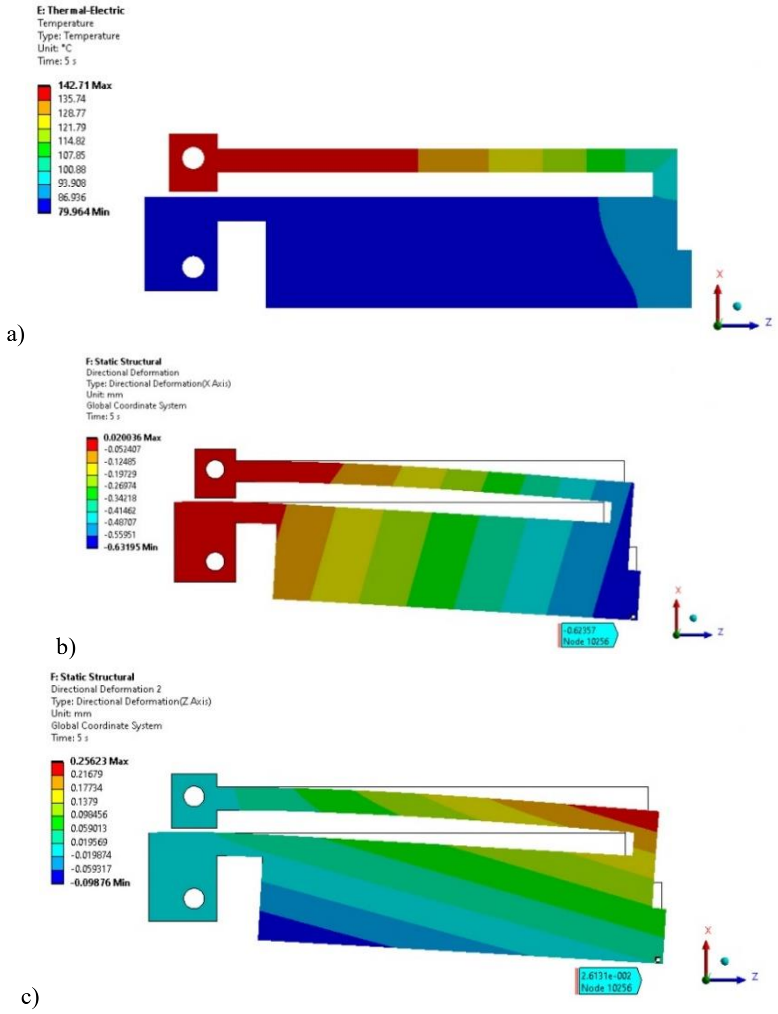


Fig. 3. Electro-thermal actuation of the actuator: a) temperature distribution b) directional deformation (X axis) and b) directional deformation (Z axis)

The calculated temperature distribution is presented in Fig. 3a, and the in-plane deflections in Fig. 3b (X axis) and Fig. 3c (Z axis). The temperature difference between the hot and cold arms is about 43°C and the maximum directional deflections corresponding to an electric actuation of 50mV were recorded at the tip of the U-shape actuator and has the value $\delta_X$=0.631 mm and $\delta_Z$=0.256 mm.

A dependence of the total displacement of the actuator with several dimensional parameters have been investigated by FEA. Thus, were defined three important parameters (Fig. 1): P1 representing the width of the hot arm, parameter P2 representing the width of the flexible part of the cold arm and parameter P3 the thickness of the actuator.

In Fig. 4 are presented the simulation results of total deformations value of the actuator with respect to the value of the parameters P1, P2 and P3.

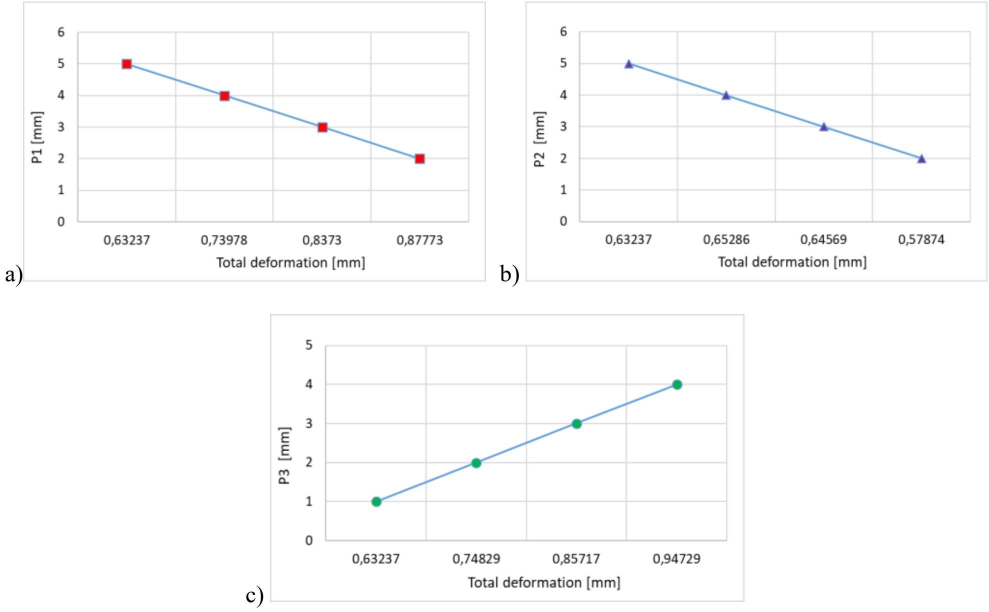


Fig. 4. Variation of the total deformation of the actuator with the dimensional parameters: a) P1, b) P2 and c) P3

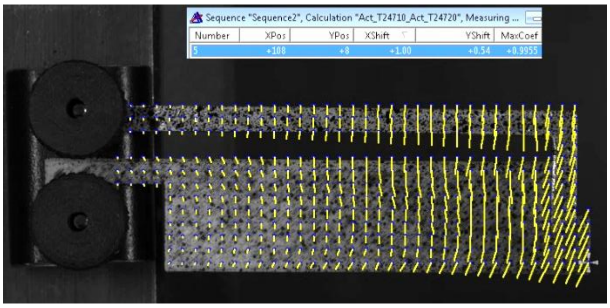
An important aspect of an actuator are the resulting forces in case of electro-thermal actuation. For the applied voltage of 50 mV the resulting actuation forces at the point of maximum deflection were $F_x$=176,4 N and $F_z$=711,3 N.

## 2.3. Experimental analysis of the actuator

Experimental analysis of the U-shape actuator manufactured by two materials was performed by the optical method of Digital Image Correlation (DIC). DIC is a powerful optical technique used to measure displacement and strain on an object's surface by analyzing images taken before and after deformation. VEDDAC (Virtual Environment for Digital Image Correlation Analysis and Characterization) is a specific software developed by Chemnitzer Werkstoffmechanik GmbH, Germany designed to facilitate DIC analysis. The experimental set-up presented in Fig. 5 consists of a high-resolution camera connected with the VEDDAC software and a thermal camera used to measure the temperature of the actuator. A random speckle pattern is applied to the surface of the object being studied. This pattern helps in tracking points on the surface during deformation. Heated up of the actuator was done by a hot air flow and the images were recorded during the cooling phase in a temperature range of 50 °C.

The results of the DIC measurements represents the pints displacements of the actuator between different images that corresponds to different temperature changes. The maximum displacement values were observed at the tip of the actuator, Fig. 6 showing the displacements vectors.

Fig. 5. Experimental set-up and the investigated actuator made of two different materials.



Sequence "Sequence2", Calculation "Act_T24710_Act_T24720", Measuring ...

| Number | XPos | YPos | XShift | YShift | MaxCoef |
|---|---|---|---|---|---|
| 5 | +108 | +8 | +1.00 | +0.54 | +0.9955 |

Fig. 6. Displacements vectors on the actuator surface measured by DIC

The values recorded after the experimental test for a temperature difference of 50 °C at the tip of the actuator were $\delta_x$=1 mm and $\delta_z$=0.54 mm.

## 3. Results and discussion

The experimental and numerical analysis of the U-shaped electro-thermal actuators revealed several key findings that provide valuable insights into their performance and optimization. Using image correlation technique, we measured the displacement of the actuator, confirming the efficacy of the proposed methodology. In comparison with the FEM for a point at the tip of the actuator (Fig. 2 and Fig. 6) the obtained displacement values were $\delta_x$=0.963 mm by FEA and $\delta_x$=1 mm by DIC (3.7% relative deviation) and $\delta_z$=0.63 mm by FEA and $\delta_z$=0.54 mm experimentally with a relative deviation of 14.2%). The DIC measurements showed close agreement with the finite element analysis results, validating the accuracy of the numerical models used.

The temperature distribution and directional deformations under both thermal and electro-thermal actuation were extensively studied. For an electric actuation of 50mV, the temperature difference between the hot and cold arms was about 44°C. The maximum directional deflections recorded at the tip of the actuator were $\delta_X$=0.631 mm and $\delta_Z$=0.256 mm, illustrating the actuator's significant response to electro-thermal inputs. Comparing with the analytical model the relative deviation of the displacement calculated with the (1) of $\delta_X=0.651$ mm was about 4.4%. It is important to mention that the temperature difference was calculated using the mean temperature in the hot and cold arms.

The influence of geometrical parameters on the actuator's performance was systematically examined. Parameters such as the width of the hot arm (P1), the width of the flexible part of the cold arm (P2), and the thickness of the actuator (P3) were varied to assess their impact on the total displacement. The results indicated that the increase the value of the P1 and P2 (width of arms) will increase the stiffness of the actuator and will decrease its total deformation. Changing the thickness of the actuator will produce higher deformations due to the bending response of the arms. Optimizing these parameters can significantly enhance the actuator's performance. For instance, variations in P1, P2, and P3 led to noticeable changes in total deformations, highlighting the importance of precise geometrical tuning.

## 4. Conclusion

The study on U-shaped electro-thermal actuators has yielded several significant conclusions, which highlight both the capabilities and the optimization potential of these devices for applications in Micro-Electro-Mechanical Systems (MEMS). Below is a detailed summary of the scientific conclusions derived from the research:

- The combined use of DIC and FEA has been validated as an effective methodology for analyzing the performance of U-shaped electro-thermal actuators. The close agreement between experimental and numerical results underscores the reliability of these techniques. Specifically, the relative deviations between DIC and FEA results were 3.7% for $\delta_x$ and 14.2% for $\delta_z$, indicating a strong correlation and validating the accuracy of the numerical models.
- Detailed analysis of temperature distribution and directional deformations under thermal and electro-thermal actuation has revealed that for an electric actuation of 50mV, the temperature difference between the hot and cold arms was approximately 43°C. The corresponding maximum directional deflections at the tip of the actuator were $\delta_X=0.631$mm and $\delta_Z=0.256$ mm, indicating significant responsiveness to electro-thermal inputs. These findings highlight the actuator's efficiency in converting thermal energy into mechanical displacement.
- The study systematically examined the influence of various geometrical parameters, such as the width of the hot arm (P1), the width of the flexible part of the cold arm (P2), and the thickness of the actuator (P3). The results demonstrated that increasing P1 and P2 enhances the stiffness of the actuator, thus reducing its total deformation, while increasing the thickness (P3) leads to greater deformations due to the bending response. These insights underscore the critical importance of precise geometrical tuning in optimizing actuator performance.
- The findings emphasize the potential for optimizing geometrical parameters to significantly enhance the performance of U-shaped electro-thermal actuators. Adjusting parameters such as arm dimensions and material properties can lead to substantial improvements in actuator efficiency and displacement capabilities. This

highlights the need for further research to refine these parameters and explore new materials that offer superior thermal and mechanical properties

Future research should focus on several key areas to advance the development and application of U-shaped electro-thermal actuators. These include:

- Exploring novel materials with better thermal and mechanical characteristics to improve actuator performance.
- Enhancing thermal efficiency through innovative design and material selection.
- Expanding the range of applications by integrating actuators into more complex MEMS devices and systems.

The study highlights the versatility of U-shaped electro-thermal actuators in MEMS technology. Their ability to generate substantial mechanical displacement efficiently makes them suitable for various applications, including optical systems, micro-robotics, biomedical devices, and precision positioning systems. This versatility underscores their potential as a key component in the future development of advanced MEMS technologies. In conclusion, the research has provided a comprehensive understanding of the performance and optimization of U-shaped electro-thermal actuators. By validating the analytical and experimental methods, identifying key parameters for optimization, and outlining future research directions, this study lays a solid foundation for the continued advancement and application of these actuators in MEMS technology.

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