53. IWK

Internationales Wissenschaftliches Kolloquium
International Scientific Colloquium

Faculty of
Mechanical Engineering

PROSPECTS IN MECHANICAL ENGINEERING

8 - 12 September 2008

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Published by
Impressum

Publisher Herausgeber	Der Rektor der Technischen Universität Ilmenau Univ.-Prof. Dr. rer. nat. habil. Dr. h. c. Prof. h. c. Peter Scharff
Editor Redaktion	Referat Marketing und Studentische Angelegenheiten Andrea Schneider
	Fakultät für Maschinenbau Univ.-Prof. Dr.-Ing. habil. Peter Kurz, Univ.-Prof. Dr.-Ing. habil. Rainer Grünwald, Univ.-Prof. Dr.-Ing. habil. Prof. h. c. Dr. h. c. mult. Gerd Jäger, Dr.-Ing Beate Schlütter, Dipl.-Ing. Silke Stauche
Editorial Deadline Redaktionsschluss	17. August 2008
Publishing House Verlag	Verlag ISLE, Betriebsstätte des ISLE e.V. Werner-von-Siemens-Str. 16, 98693 Ilmenau

CD-ROM-Version:

Implementation Realisierung	Technische Universität Ilmenau Christian Weigel, Helge Drumm
Production Herstellung	CDA Datenträger Albrechts GmbH, 98529 Suhl/Albrechts

ISBN: 978-3-938843-40-6 (CD-ROM-Version)

Online-Version:

Implementation Realisierung	Universitätsbibliothek Ilmenau ilmedia Postfach 10 05 65 98684 Ilmenau

Home / Index:
http://www.db-thueringen.de/servlets/DocumentServlet?id=17534

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Bistable Clamping Mechanism for Use in a Microstructured Electrothermal Inchworm Plattform

Introduction

Aiming to overcome the dynamic range problem of limited displacements at high resolution, the concept of a monolithic linear stepping motor based on the Inchworm principle has been presented in [1]. Four piezoelectric actuators are used to alternately clamp and move a slider resulting in a range of motion up to 20 mm. Fig. 1 shows the assembled platform fabricated from a stainless steel sheet by laser cutting. The piezo stacks have been inserted manually.

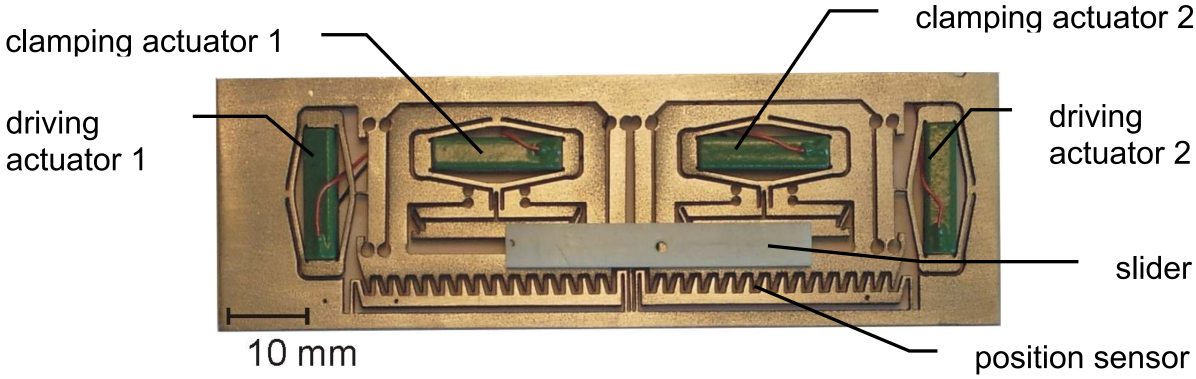


Fig. 1: Piezoelectric Inchworm Platform

In order to fully tap the miniaturization potential of this Inchworm platform, high-aspect-ratio UV-lithography using the epoxy-based negative resist SU-8 has been introduced allowing for batch fabrication of several devices on a four inch Silicon substrate (Fig. 2). In this approach the fully crosslinked SU-8 is used as the structural material due to its mechanical properties and ease of fabrication.

As a consequence of miniaturization, the piezo stacks have been replaced by electrothermal bent-beam actuators allowing for large forces and displacements while being compatible with micro-fabrication [2]. In order to increase the overall efficiency of the thermally actuated Inchworm Platform, modification of the clamping mechanisms, in a way that bistable behaviour is achieved, has been investigated.

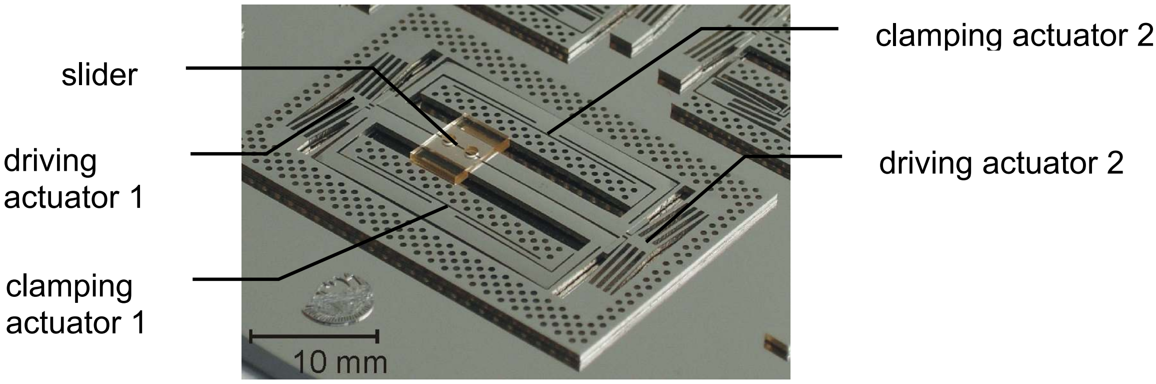


Fig. 2: Micro-fabricated electrothermal Inchworm Platform

Bistable Mechanisms Made of SU-8

Bistability is the property of a mechanical system which allows it to rest in two stable positions without the influence of external forces. Small perturbations from these stable positions lead to oscillations around the equilibrium. This behaviour is often illustrated by the ball-on-a-hill analogy as shown in Fig. 3a [3].

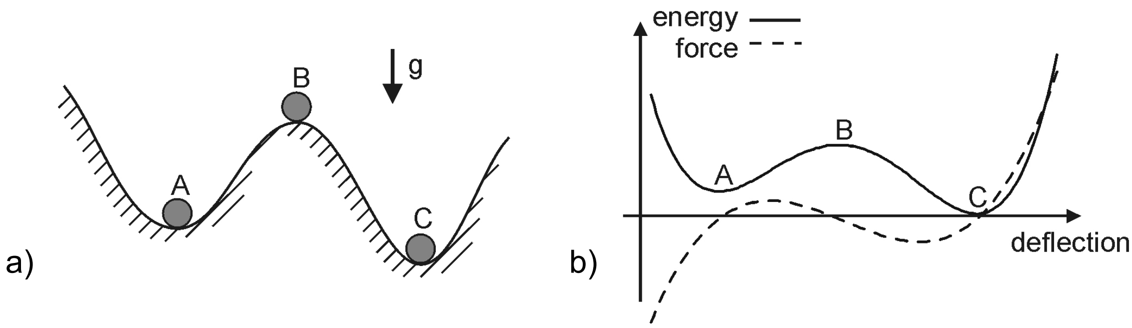


Fig. 3: a) Ball-on-a-hill as example for bistability, b) energy and force-deflection characteristics of a bistable mechanism

A given mechanism can be tested for bistability by plotting its potential energy against deflection: A bistable System features two minima – points A and C in Fig. 3b – and at least one maximum – point B in Fig. 3b – in its energy curve. Accordingly, three zero-crossings can be found in the force-deflection diagram, which is computed as the derivative of the potential energy.

$$\frac{dW}{dx} = F \tag{1}$$

The inflection points of the energy curve indicate the maximum and minimum force, respectively.

In order to investigate the possibility of building bistable mechanisms using crosslinked SU-8, a double-beam snap-through mechanism as shown in Fig. 4 has been analyzed.

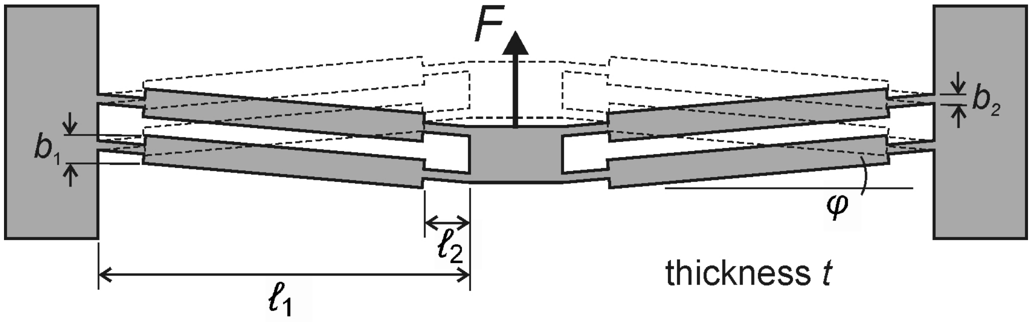
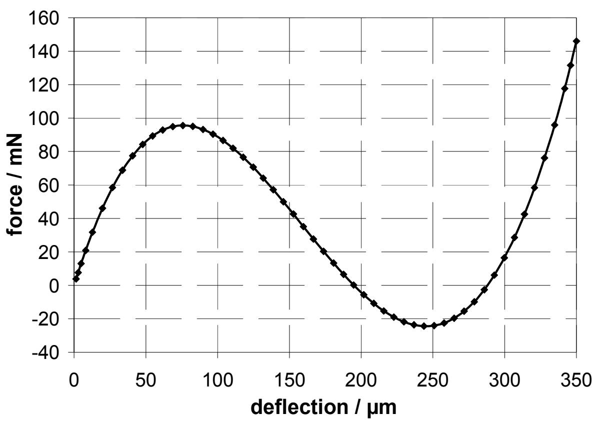


Fig. 4: Double-beam snap-through mechanism with its two stable positions

When moving from one stable position to the other, the mechanism stores and releases potential energy in its compliant elements, i.e. an energy barrier has to be overcome. This barrier prevents the mechanism from snapping back to its original state.

The motion of the compliant members typically involves geometric nonlinearities such as large deflections and stress stiffening as well as varying force and moment loading conditions. This generally prevents analytical description. Therefore nonlinear two-dimensional finite element analysis (ANSYS® 11.0) is used to obtain the force-deflection characteristics of the structures of interest. A Young's modulus of $E_{SU\text{-}8}$ = 3 GPa has been calculated from the bending of cantilever test structures using a measurement setup consisting of a voice-coil actuator and a laser displacement sensor. The Poisson's ratio is inserted as $\nu_{SU\text{-}8}$ = 0,22. Von-Mises stress is evaluated to insure that the yield strength reported in the range 50–70 MPa [4, 5] is not exceeded. Fig. 5 shows the force-deflection characteristics of the optimized double-beam snap-through mechanism together with the associated geometry parameters defined in Fig. 4.



Parameter	Value
ℓ_1	2 mm
ℓ_2	250 µm
b_1	150 µm
b_2	50 µm
t	500 µm
φ	5 °

Fig. 5: Force-deflection characteristics of the double-beam snap-through mechanism

Bistable Clamp with Electrothermal Actuation

In order to realize a bistable clamp, two double-beam snap-through mechanisms are combined with two electrothermal bent-beam actuators for opening and closing as shown in Fig. 6.

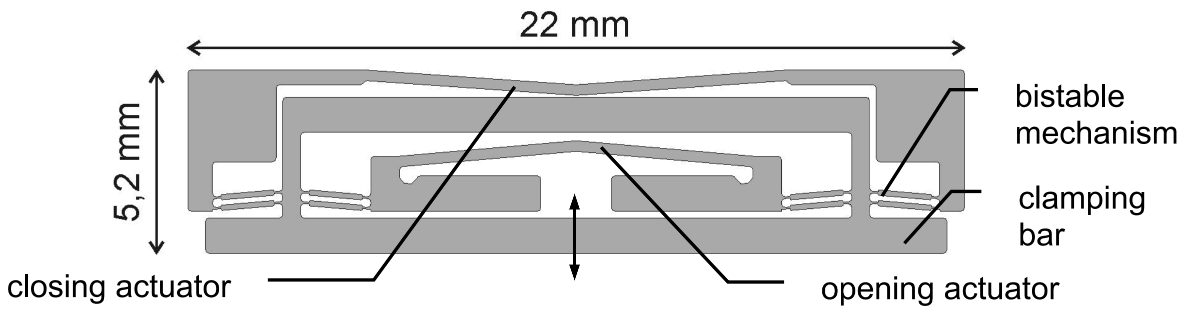


Fig. 6: Layout of the bistable clamping mechanism (counter bearing not shown)

Compared to the single mechanism (Fig. 5) the resulting reaction forces are increased, reaching -50 mN and 150 mN at the two extrema. At the same time, the overall displacement remains almost unchanged at approximately 300 µm (Fig. 7).

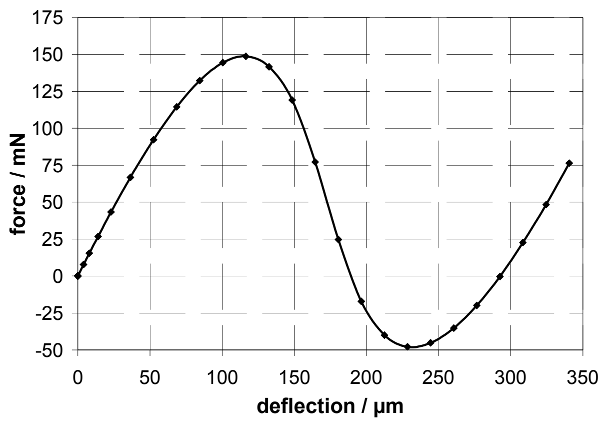


Fig. 7: Force-deflection characteristics of the clamping mechanism

The electro-thermo-mechanical system is analyzed using 3-dimensional, nonlinear coupled field finite-element simulation [2].

Fabrication Process

Fig. 8 shows an overview of the fabrication sequence in which an electrodeposited sacrificial copper layer is used to realize movable parts. In a first step, a thin Cr/Cu seed layer is sputtered on a 100 mm silicon substrate (Fig. 8a). Then a 30 µm thick layer of AZ9260 positive resist is spincoated and lithographically patterned to define the stationary parts including actuator pads and frame (Fig. 8b). This layer is electrochemically filled with the sacrificial copper (Fig. 8c). After planarization of the copper layer, the

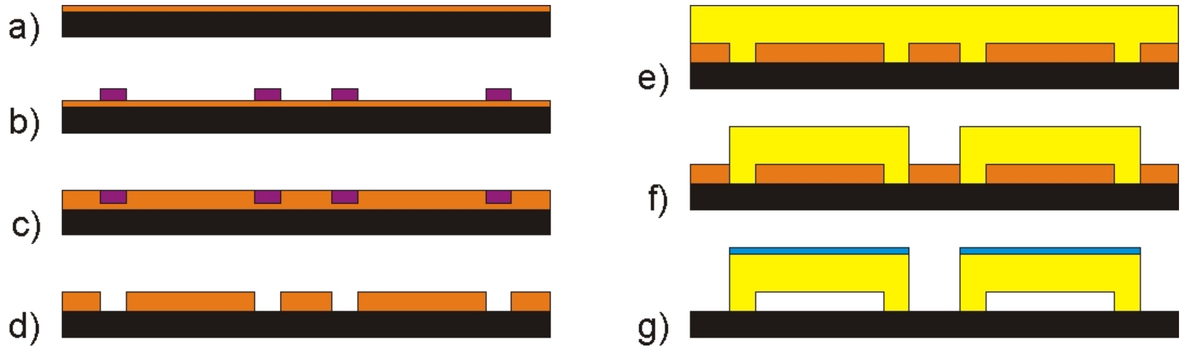


Fig. 8: Process overview: a) substrate pre-treatment and sputter deposition of Cr/Cu-seed layer, b) AZ9260 lithography (mask 1), c) electrodeposition and planarization of sacrificial Cu layer, d) AZ removal, e) SU-8 spin coating, f) SU-8 exposure and development, g) metallization

positive resist is stripped and the seed layer is etched (Fig. 8d), before a 500 µm thick layer of SU-8 is applied (Fig. 8e), softbaked and exposed through a second mask defining the suspended elements (Fig. 8f). The SU-8 is then crosslinked during PEB, slowly cooled down to room temperature and developed using megasonic agitation. After a short hardbake, the copper is etched using iron(III) chloride. Finally, a thin aluminium film is applied through a shadow mask to realize the electrothermal actuators (Fig. 8g). Fig. 9 shows SEM pictures of the fabricated double beam mechanism and a detail view of the two electrothermal bent-beam actuators.

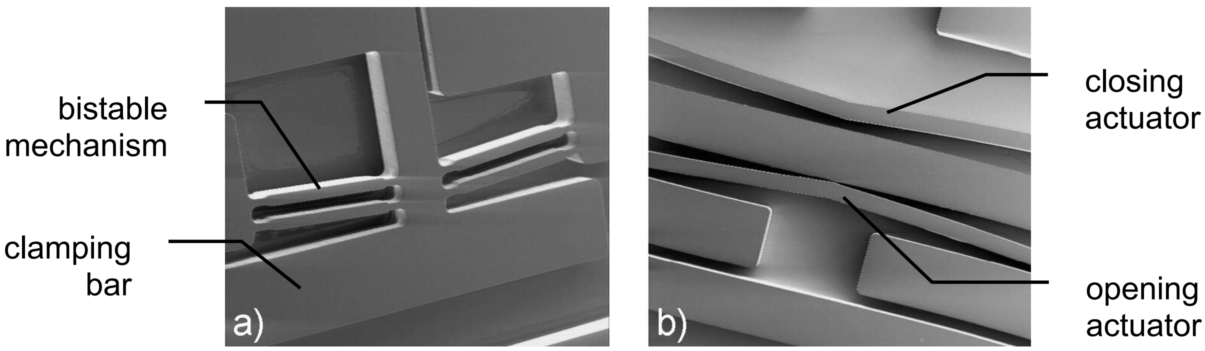


Fig. 9: a) double beam bistable mechanism, b) electrothermal bent-beam actuators

Preliminary Results and Model Improvement

The fabricated mechanisms have been investigated for bistable behaviour and electrothermal actuation, respectively. Fig. 10 shows photographs of the double-beam mechanism in both of its stable positions. The observed deflection in the range 320–375 µm is slightly larger than predicted by FEM.

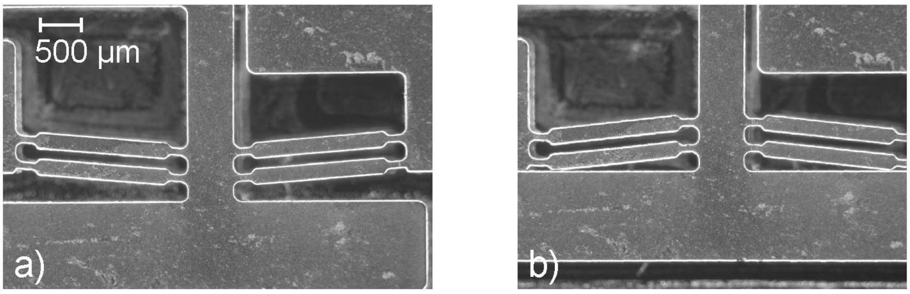


Fig. 10: SU-8 snap-through mechanism, a) first stable position as manufactured, b) second stable position

However, only a small yield rate could be achieved for the fabricated test mechanisms, since not all of them showed the desired behaviour. Moreover, bistability was generally limited to several switching cycles, before the compliant hinges fractured due to high bending stress. This deviation from simulation results can be attributed to neglecting of thermal stress within the structural SU-8 layer in the FE simulations. The main part of the tensile stress is introduced during cool-down from post exposure bake (PEB) at 95 °C due to the mismatch of thermal expansion coefficients (TEC) between SU-8 and the silicon substrate. It leads to preloading in the idle state and therefore the yield stress is reached at smaller deflections than predicted by the simple model. The inherent stress stiffening effect results in larger restoring forces of the compliant members. This is the main reason why bistability is not achieved for every mechanism.

Bistability as well as reproducibility could be improved by lowering the PEB temperature to 60 °C for an extended time, in order to reduce the thermal stress. However, this approach at the same time reduces the stiffness of the electrothermal actuators and therewith achievable actuator forces.

Consequently, the finite element model is improved by including the material dependent reference temperature T_{ref} at which the structure is almost stress-free together with the thermal expansion coefficient of SU-8. In order to clarify contradictory values from literature [6, 7], the TEC of SU-8 in the relevant temperature range 20–260 °C is obtained from the thermal strain of rectangular test structures on a horizontal push-rod dilatometer

(NETZSCH DIL 402C, Fig. 11a). As a worst case estimate the PEB temperature can be used as reference temperature for SU-8.

$$T_{\mathrm{ref,SU\text{-}8}} = T_{\mathrm{PEB}} = 95\ °\mathrm{C} \tag{2}$$

However, since crosslinking already starts at much lower temperatures and the FE model does not consider any stress relaxation, it is more reasonable to choose $T_{\mathrm{ref,SU\text{-}8}}$ = 45–65 °C. Fig. 11b) shows the effect of the included thermal stress on the force-deflection characteristics of the double-beam mechanism. With increasing reference temperature the minimum force near the desired second stable position F_{min} is reduced considerably. For T_{ref}>35–40 °C bistability is not achieved anymore.

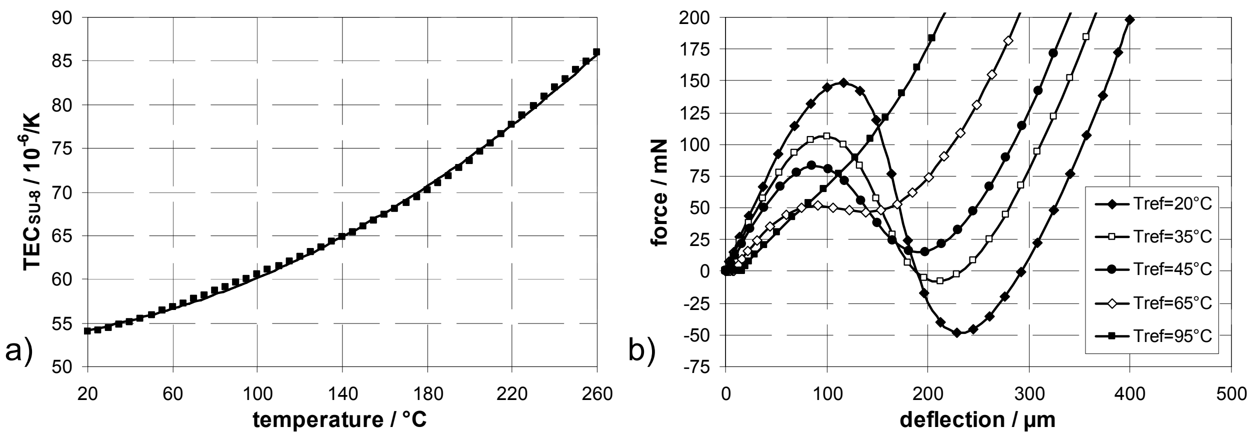


Fig. 11: a) TEC of SU-8 measured by dilatometry, b) effect of thermal stress on mechanism characteristics

With the revised FE model thermal stress can now be incorporated in future designs allowing for mechanisms with reproducible bistable behaviour. However, since the design space is further restricted, lower maximum and minimum forces are expected.

Conclusion

The principle possibility to realize bistable mechanism made of crosslinked SU-8 has been shown. However for reliable results, it is important to consider the tensile stress resulting from TEC mismatch in the design process. With the revised FE model future work will concentrate on the design and fabrication of an electrothermally actuated bistable clamping mechanism suitable for application in the presented micro-structured linear stepper motor. Fig. 12 shows a possible layout.

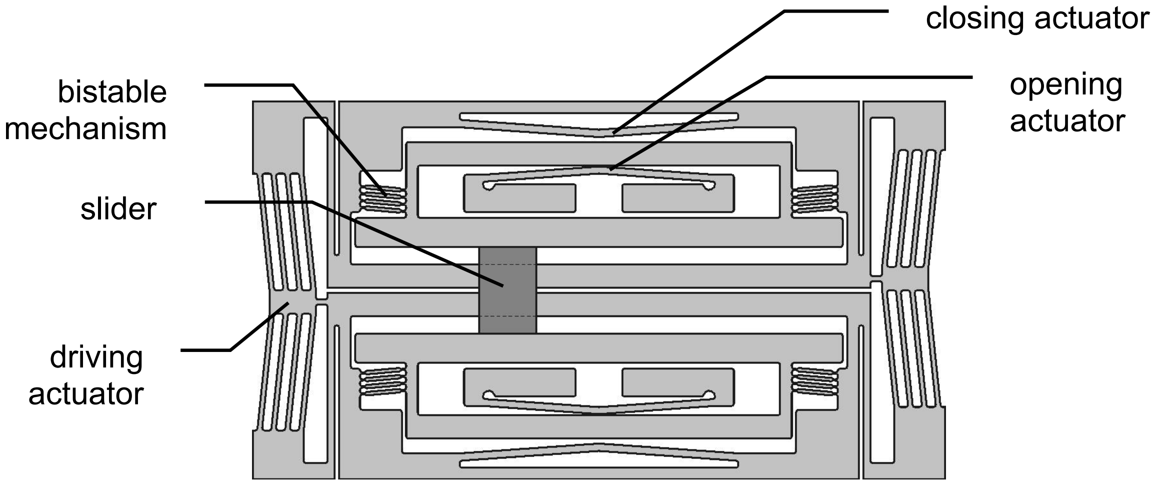


Fig. 12: Possible layout of an electrothermal Inchworm Platform with bistable clamping mechanism (electrodes not shown)

Acknowledgement

The authors wish to thank Dr. Blumm and Dr. Meyer at NETZSCH-Gerätebau GmbH for the experimental evaluation of the thermal expansion coefficient for SU-8 samples fabricated in our laboratory.

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