Systematic Design and Optimization of Multi-Material, Multi-Degree-of-Freedom Micro Actuators

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ABSTRACT

The paper reports an automated method for the synthesis of multi-material, multi-degree-of-freedom micro actuators. The method is based on topology optimization, an iterative computational scheme consisting of alternating finite element analyses, sensitivity analyses and optimal material redistributions.

Keywords: Actuators, MicroElectroMechanical Systems (MEMS), Topology Optimization, Finite Element Analysis.

1 INTRODUCTION

Manufacturing and processing techniques for MEMS have reached a high level of maturity and new devices can be built in a manner of days in labs and fundries. In contrast to that, modelling and especially development of *systematic* design methods is still subject to intense research. Due to the lack of existing systematic design methods for MEMS, many devices are designed using intuition, experience and trial and error approaches. Furthermore, many devices are build from rectangular sub–elements ordered in "Manhattan"-like horizontal/vertical grids. Obviously, systematic design methods should be able to improve existing designs considerably and come up with entirely new or more efficient devices with increased functionality.

A promising method which may be able to solve some of above mentioned problem is the *topology optimization method.* The topology optimization method [1], [2] was originally developed for large scale structural design problems and is an iterative numerical method consisting of alternating finite element analyses, sensitivity analyses and material redistribution. The topology optimization method solves the problem of distributing material phases freely in a design domain such that some performance or functionality criterion is maximized.

Topology optimization has recently been applied to the synthesis of passive MEMS [3]–[5] and to active MEMS using electrothermomechanical actuation [6]. In the latter, it was shown how topology optimization can be used as an efficient design tool for microactuator synthesis by improving the performance of existing designs by up to a 100%. Fabrication and testing of actuators synthesized by a one-material version of the software has been reported [7], [8].

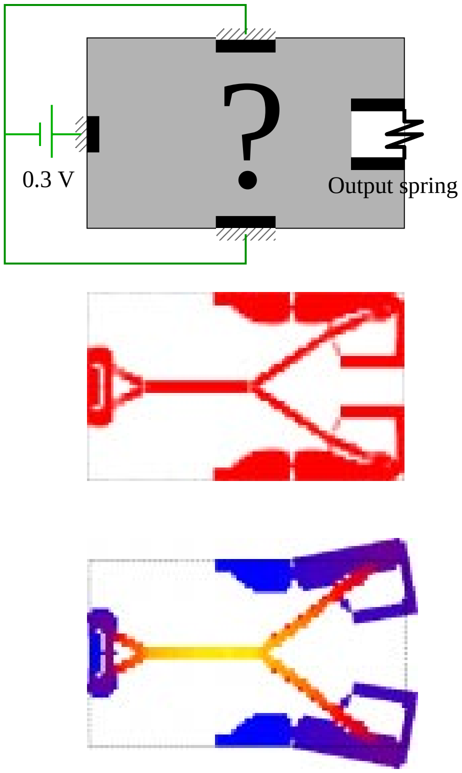


Figure 1: Top: Definition of design domain (grey region) for micro gripper example. Black areas denote regions fixed to be solid and white areas denote regions fixed to be void. Center: Topology optimized one-material micro gripper. Bottom: deformation pattern and temperature distribution of the optimized actuator

This paper will discuss the extensions, theory and implementation aspects of the method applied to the synthesis of electrothermomechanical actuators with multiple degrees of freedom. Two examples illustrate the efficiency of the method and demonstrate the gains that can be obtained by introducing a second material in the design.

2 THEORY

The goal of the topology optimization algorithm is to design actuators that maximize the output displacement u_{out} of one or more workpieces of given stiffnesses for fixed input voltages and with constraints on input currents. The procedure is initiated by discretizing the design domain (e.g. Fig. 1, top) into a number (N from 1.000 to 10.000) of finite elements. For one-material design, the relative density of material in each element is a design variable. For two-material design, there are two design variables per element which determine whether there is material in the element or not and the material type, respectively. Several constraints such as zero-cross-axes sensitivity and bounds on material volumes are imposed in order to get realistic and useful designs.

An optimization problem for a one-degree-of-freedom two-material actuator can be written as

$$\left.\begin{array}{rl} \displaystyle\max_{\boldsymbol{\rho}_1,\ \boldsymbol{\rho}_1} : & u_{out}(\boldsymbol{\rho}_1,\ \boldsymbol{\rho}_2) \\ \text{s.t.} : & V_1^e(\boldsymbol{\rho}_1, \boldsymbol{\rho}_2) = \displaystyle\sum_{e=1}^{N} \rho_1^e\ \rho_2^e V^e\ \leq\ V_1^* \\ : & V_2^e(\boldsymbol{\rho}_1, \boldsymbol{\rho}_2) = \displaystyle\sum_{e=1}^{N} \rho_1^e\ (1-\rho_2^e) V^e \leq V_2^* \\ : & I(\boldsymbol{\rho}_1,\ \boldsymbol{\rho}_2) \leq I^* \\ : & \frac{(\hat{u}_{out}(\boldsymbol{\rho}_1,\ \boldsymbol{\rho}_2))^2}{(u_{out}(\boldsymbol{\rho}_1,\ \boldsymbol{\rho}_2))^2} \leq \epsilon^* \\ : & \mathbf{0}\ <\ \boldsymbol{\rho}_{min} \leq \boldsymbol{\rho}_1 \leq \mathbf{1} \\ : & \mathbf{0}\ \leq \boldsymbol{\rho}_2 \leq \mathbf{1} \\ : & \text{equilibrium equations} \end{array}\right\}, \quad (1)$$

where ρ_1^e and ρ_2^e are the element design variables ordered in the N-vectors $\boldsymbol{\rho}_1$ and $\boldsymbol{\rho}_2$, respectively, V^e is the element volume, V_1^* and V_2^* are the constraints on material volumes, I is the electrical current, I^* is the upper bound for the current. In some cases, the volume constraint on each material phase is substituted with an overall volume constraint

$$V_1^e(\boldsymbol{\rho}_1,\ \boldsymbol{\rho}_2) + V_2^e(\boldsymbol{\rho}_1,\ \boldsymbol{\rho}_2) = \sum_{e=1}^{N} \rho_1^e\ V^e\ \leq\ V^*. \quad (2)$$

For problems with multiple electrical inputs and multiple output points, extra constraint functions can be added to the optimization problem. For more details on the algorithm and its implementation, the reader is referred to the references by Sigmund.

The design algorithm is implemented in the FORTRAN90 programming language. A simple in-data file allows for easy definition of design problems, geometries, material data and constraints. A graphical output showing electric, thermal and displacement fields for various load cases together with design changes allows the user to follow the progress in the design.

A typical iterative design process may require from a couple of hours to a couple of days of CPU-time on a fast computer (PC or workstation) and may consist in several thousand material redistributions.

3 EXAMPLES

3.1 One degree-of-freedom gripping mechanism

The design domain ($w \times h \times t = 500\mu m \times 300\mu m \times 12\mu m$) is shown in Fig. 1(top). An electric field is applied between the top and bottom terminals and the left terminal. 30% of the design domain can be filled with Nickel and the objective is to maximize the work on the spring with a constraint on the resistance. Fig. 2 shows the effect of introducing a second material in the design. It is seen that the introduction of a material with less electrical conductivity or Young's modulus hardly changes the performance, whereas the introduction of a material with half the thermal conductivity greatly improves the performance.

3.2 Two degree-of-freedom scanning mechanism

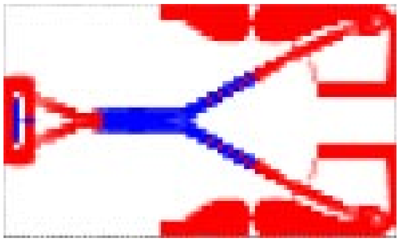
The design domain ($w \times h \times t = 500\mu m \times 400\mu m \times 12\mu m$) is shown in Fig. 3(top). The goal is to move the output point in the horizontal direction for the green electric input and in the vertical direction for the red electric input. The cross-sensitivity is constrained to be less than 10%. The figure shows the optimized one- and two-material structures as well as displacement patterns and temperature distributions for the two-material actuator.

4 MANUFACTURING AND TESTING

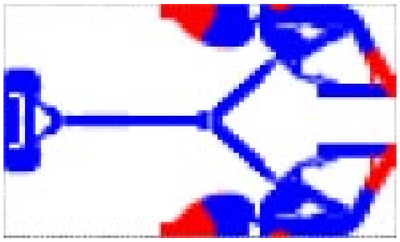
The theoretical designs are being verified experimentally at Mikroelektronik Centret (MIC), at the Technical University of Denmark (DTU). Tests of a one-material, 2 DOF actuator manufactured by laser-micromachining and electro-plating showed good agreement with theoretical predictions [8]. Manufacturing techniques for two-material structures are currently being developed.

5 CONCLUSIONS

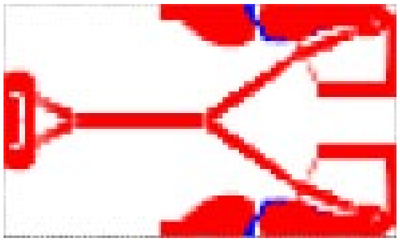
This extended abstract has given a very brief introduction to topology optimization of two-material, multi-degree-of-freedom compliant microactuators. For more details on the theory, the implementation and examples, the reader is referred to an up-coming trilogy paper [9]–[11] or the other references by Sigmund and for more details on manufacturing and testing of topology optimized microactuators the reader is referred to the references by Jonsmann [7], [8], [12].



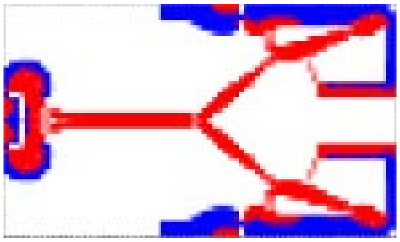
🟦 Half electrical conductivity (1%)



🟦 Half thermal conductivity (57%)



🟦 Half Young's modulus (1%)



🟦 Half thermal expansion (4%)

Figure 2: Topology optimized two-material micro grippers. The blue material has half electrical conductivity, Young's modulus, thermal conductivity and thermal expansion coefficient, respectively, compared to the red phase (pure Nickel). Numbers in parentheses indicate improvement in output work compared to the one-material actuator shown in Fig. 1.

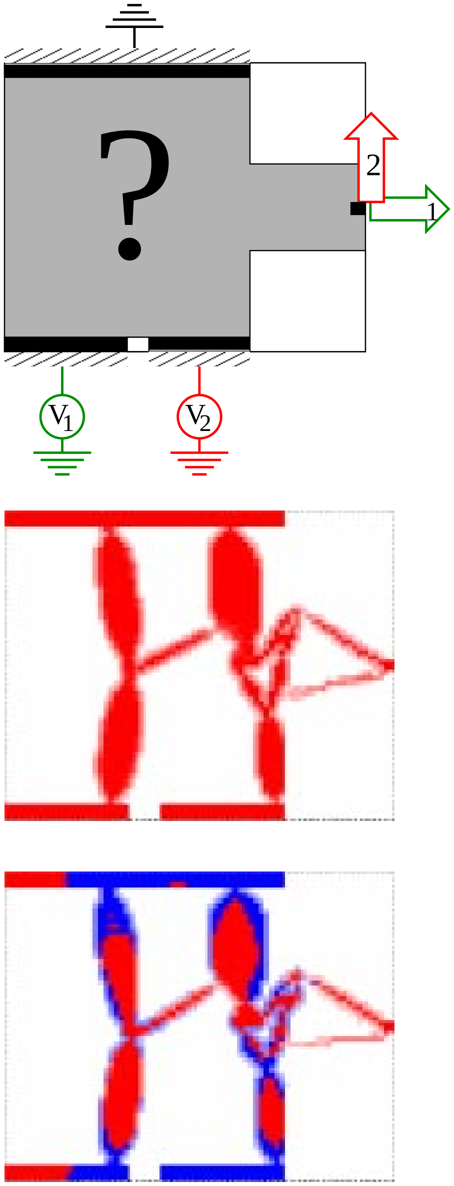


Figure 3: Top: design domain for a 2DOF micro-scanner. Center: topology optimized actuator composed of Nickel and bottom: topology optimized two-degree-of freedom actuator composed of Nickel (red) and a material (blue) with half the Young's modulus and half the thermal conductivity of Nickel. The improvement in output force and displacement from introducing a second material in the the design is more than 40%.

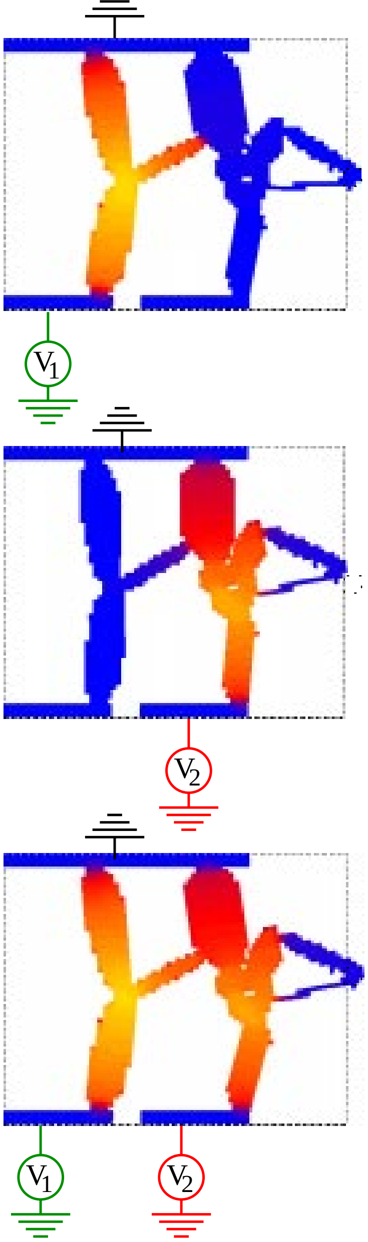


Figure 4: Actuated modes with temperature distributions for the two-degree-of-freedom, two-material actuator from Fig. 3.

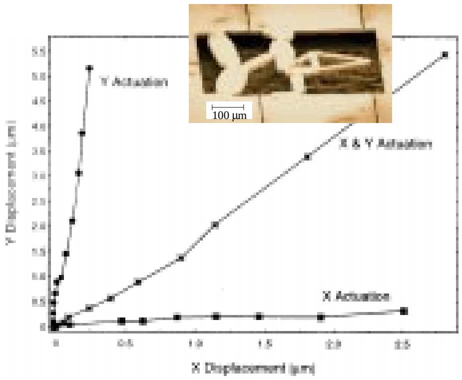


Figure 5: The one material actuator from Fig. 3(center) has been manufactured and tested at MIC (Mikroelektronik Centret) at the Technical University of Denmark (DTU). Courtesy of J. Jonsmann and S. Bouwstra.

6 ACKNOWLEDGMENTS

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REFERENCES

[1] M. P. Bendsøe and N. Kikuchi. Generating optimal topologies in optimal design using a homogenization method. *Computational Methods in Applied Mechanics and Engineering*, 71:197–224, 1988.

[2] M. P. Bendsøe. *Optimization of Structural Topology, Shape and Material.* Springer, 1995.

[3] G. K. Ananthasuresh, S. Kota, and Y. Gianchandani. A methodical approach to the design of compliant micromechanisms. In *Solid-state sensor and actuator workshop*, pages 189–192, 1994.

[4] U. D. Larsen, O. Sigmund, and S. Bouwstra. Design and fabrication of compliant mechanisms and material structures with negative Poisson's ratio. *Journal of Microelectromechanical Systems*, 6(2):99–106, June 1997.

[5] O. Sigmund. On the design of compliant mechanisms using topology optimization. *Mechanics of Structures and Machines*, 25(4):495–526, November 1997.

[6] O. Sigmund. Systematic design of electrothermomechanical microactuators using topology optimization. In *Modelling and Simulation of Microsystems, Semiconductors, Sensors and Actuators*, pages 350–355, Santa Clara, California, 1998. MSM98.

[7] J. Jonsmann, O. Sigmund, and S. Bouwstra. Compliant electro-thermal microactuators. In *MEMS'99*, pages 588–593, 1999.

[8] J. Jonsmann, O. Sigmund, and S. Bouwstra. Multi degrees of freedom electro-thermal microactuators. In *TRANSDUCERS'99*, pages 1372–1375, 1999.

[9] O. Sigmund. Design of multiphysics actuators using topology optimization - part I: One-material structures. *Submitted*, 2000.

[10] O. Sigmund. Design of multiphysics actuators using topology optimization - part II: Two-material structures. *Submitted*, 2000.

[11] O. Sigmund. Design of multiphysics actuators using topology optimization - part III: Large displacements. *Submitted*, 2000.

[12] J. Jonsmann. *Technology Development for Topology Optimized Thermal Microactuators.* PhD thesis, Technical University of Denmark, Mikroelektronik Centret (MIC), December 1999.