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FINITE ELEMENT METHOD-BASED ELECTRO-THERMO-MECHANICAL ANALYSIS OF UNIMORPH ACTUATOR FOR MICROROBOTS APPLICATION

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***Abstract*—**This research presents modeling and simulation findings of a unimorph that can enhance displacement and temperature for rising applied current. In MEMS (Micro-Electro-Mechanical Systems) the development of analytical models to describe the motion of unimorph actuators is hampered by their significant nonlinearities and intricate geometries. This problem can be solved successfully using finite element modeling, which also enables performance prediction and soft actuator design optimization. Investigating the deformation in unimorph actuators for various applied currents is the major goal of this work. With an increase in actuator applied current, deformation rises. The microstructure is transformed into a unimorph actuator as a result of current-induced thermal strain and thermally induced deformation. The actuator was designed for high force-displacement and modeled with a 20 μm width and 110 μm length U-shaped microstructure and has been tested using currents up to 20 mA, thus observing temperature rise upto 310 °C with deformation of maximum 3.6 μm along the axis. This article's presentation of modeling techniques, material characteristics, and design principles can be used as a springboard for designing soft robotic actuators.

***Keywords*—**Actuators, finite element method, MEMS, microrobots, softrobots.

I. INTRODUCTION

OVER the past two decades, the number of papers on soft robotics has grown exponentially. Soft robots made of hydrogels, electroactive polymers, and elastomers are physically robust and can adapt to delicate items and environments due to their conformal deformation, in contrast to stiff traditional manipulators[1]. They exhibit improved safety and accuracy and can be utilized in confined spaces with limited access because they are tiny[2], [3]. Many soft robots have ecologically inspired designs, including those of fish, manta rays, tentacles, worms, snakes, and worms[4]–[7]. Applications vary from minimally invasive operations to handling sensitive goods and safe human-robot contact to physiotherapy and help for the aged[8]. The soft robotics toolset covers key aspects of soft robotics architecture, manufacturing, analysis, and controlling. Soft actuators serve as the foundation for soft robotics. One active layer and one inactive layer form a unimorph actuator where the active layer normally is piezoelectric and the passive layer can be formed from a polymeric layer or non-piezoelectric material. This microstructure is then supported at one end and the application of an electric field may cause deformation in that active layer.

Unimorph actuators' nonlinearities can be handled well without the use of an explicit analytical model thanks to finite element modeling (FEM)[9]. Additionally, the FEM is not restricted to the thin structures required by the theory of Cosserat, the piecewise constant curvature assumption, or the Euler-Bernoulli beam theory for simulating bending motion. In addition, FEM can provide some advantages in the simulation process. Firstly, FEM can handle the significant material nonlinearities and deformations that occur during the compression of the unimorph actuator[10]. Secondly, FEM can be used to assess the capabilities and constraints of unimorph actuator designs under assorted inputs and foresee performance[11]. As the production of actuators takes a lot of time, a quick and effective design framework cuts down on costs and development time effectively[12]. Furthermore, FEM can help us better understand how strain and stress are distributed with the

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varying induced current and thermal transfer system in soft actuators. By using this capability, one can, for instance, identify probable areas of fatigue and gain a better knowledge of the impact of local strain on overall actuator performance in the application of modern technologies. On top of that, surfaces that come into touch during deformation can have contact nonlinearities that FEM can handle in the simulation procedure[13].

In this work, we are going to design an electro-thermal-solid mechanic's combined Multiphysics based microstructure of a unimorph actuator in a MEMS-based simulation tool named COMSOL Multiphysics. The geometry of the structure is designed in this platform and then proper material has been designated in the geometrical structure. Material properties like Electro-thermal characteristics along with mechanical properties have been declared in the material section and solid mechanics, heat transfer in solids and electrical current combined physics has been declared in the structure to simulate the bending characteristics of the actuator. Consequently, physics-controlled mesh analysis has been done, and time-independent stationary analysis is done to get the results in terms of temperature distribution, stress-strain analysis, voltage distribution, electrical field analysis, isothermal properties analysis, and finally showing the relation between the displacement of the actuator with the variation of the applied current.

II. ACTUATOR DESIGN AND MODELING

The goal of the simulation is to determine the structure's deformations due to thermal expansion which is caused by electrical current. Then due to the applied current, the deformations and stress-strain analysis will be presented. At room temperature, the actuator was regarded as having a significant thermal mass. This establishes a boundary condition of constant temperature at one side of the actuator and also a box has been designed in such a way that it will provide room temperature to understand the thermal analysis of conduction and convection during the simulation. Due to the limited electrical resistance of the structural material with polysilicon IP-S, the device gets heated by the Joule effect as the electrical current passes through the actuator's arms. A difference in electric potential was added as a boundary condition between the actuator's contact pads for the electrical thermal simulations. For understanding the deformation, the solid mechanics' profile has been evaluated and to declare the boundary condition one side of the unimorph actuator along with the boundary with the airbox has been selected as a fixed constraint. The unimorph actuator has two layers from which one layer is active or piezoelectric properties based and the other one is a passive layer that is made from a polymeric layer (IP-S). The length and width of the actuator are 110×20 μm^2. Both the active and passive layer has the same length and width but the thickness of the IP-S layer is 15 μm whereas the active layer thickness is 1 μm. The schematic diagram of the unimorph actuator has been shown in Fig. 1.

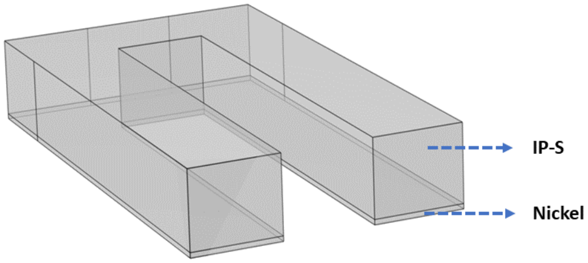


Fig. 1. Schematic illustration of the proposed unimorph actuator.

For simulation and thermal analysis, an airbox has been occupied with a size of 90×130×50 μm^3 which helps to understand thermal modeling, especially thermal conduction, and thermal convection. The box with the proposed device has been shown in Fig. 2.

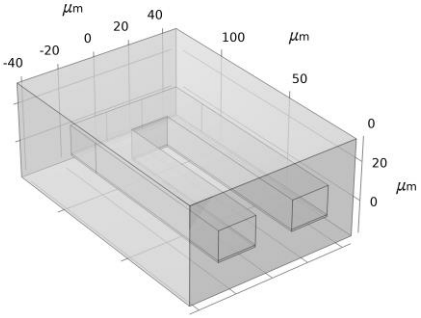


Fig. 2. Proposed unimorph actuator in three-dimensional air-box environment for heat transfer module.

Different material parameter and their properties have been taken from the literature and the parameter has been shown in Table 1.

TABLE 1
Parameter used in COMSOL Simulations

Parameter	IP-S	Nickel
Density [kg/m³]	1112	6505
Thermal conductivity [W/(m·K)]	0.31	8.605
Heat capacity at constant pressure [J/(kg·K)]	1505	3710

Coefficient of thermal expansion [1/K]	52e-6	7.6e-6
Young's modulus [Pa]	4.05e9	106.009e9
Poisson's ratio [1]	0.31	0.33
Electrical Conductivity [S/m]	-	1.33e6

Three sets of governing laws—electrostatics, heat transfer statics, and mechanical statics—are used in Joule's heating and Thermal Expansion simulation while building an actuator. For solid mechanics, the following equation is considered.

$$0 = \nabla . s + Fv \qquad (1)$$

Here, s is the stress and F is the deformation gradient and v means the displacement field. In solid mechanics, the flow of applied current creates stress and strain in the unimorph actuator[14]. Simply anchoring at the fixed restrictions of the actuator's one side next to the airbox and setting zero displacements on the z-axis defines the boundary condition of this equation. owing to the use of applied electric current and thermal analysis therefore, it is possible to obtain the displacement distribution.

For heat transfer in solids,

$$\rho C_p u . \nabla_T + \nabla . q = Q + Q_{ted} \qquad (2)$$

$$q = -k \nabla_T \qquad (3)$$

Where, ρ is the density, C_p is the constant pressure heat capacity, k is thermal conductivity and q is the amount of heat transferred. When evaluating the characteristics of solids and fluids, the effective volume heat capacity is used as the coefficient in Equation (2), which represents the change in temperature over time. Convection, which is the second word, is the change in heat caused by a reaction velocity field. The heat conduction term, which indicates the heat change in heat conduction, is the third term. Fourier's law of thermal conductivity, or the change in heat caused by effective thermal conductivity, is expressed in Equation (3)[15].

Under circumstances where inductive effects are minimal, the Electric Currents interface computes electric field, current, and potential distributions in conducting mediums. The scalar electric potential serves as the dependent variable in the current conservation equation based on Ohm's law that is solved by the Electric Currents interface the following equations are derived.

$$\nabla . j = Q_{j,v} \qquad (4)$$

$$J = \sigma E + J_e \qquad (5)$$

$$E = -\nabla v \qquad (6)$$

Where, E is electric field intensity, J current density, v electric potential, J_e is externally generated current density, σ is electrical conductivity, $Q_{j,v}$ is current sources[16]. The electric current is specified as a parameter and ranges from 1 to 20 mA in steps of 1 mA, depending on the simulation. The boundary condition is specified in two corners of the structure as ground and terminal. To numerically solve the coupled model using the finite element method, the entire cell structure has been meshed with a variable mesh element size. The mesh of the construction is depicted in Fig. 3. With the sweep mesh method, specific layers might have a smaller mesh, while layers like the air top block can have a coarser mesh. As a result, the entire unimorph actuator structure as well as the interface between the metallic contact and the air box structure have been produced with a physics-controlled mesh. Initial testing, however, shows that this element size won't have a big impact on the simulation's outcomes. A meshing sequence was established to increase the results' accuracy and shorten computation times. After successful physics declaration in the structured geometry of the proposed device, a physics-controlled mesh analysis has been done and it is shown in Fig. 3.

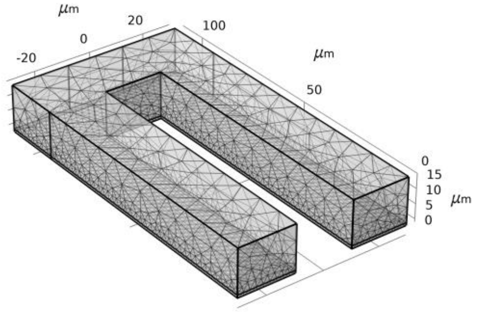
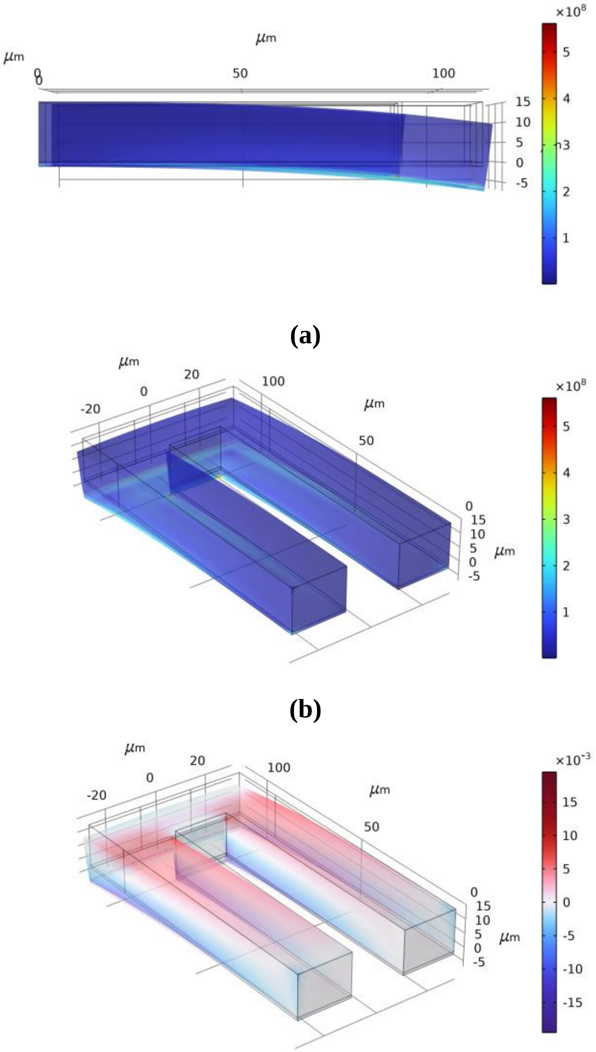


Fig. 3. Physics-controlled mesh analysis of the proposed model.

For the study, a time-independent stationary study has been taken where electromagnetics calculates direct currents, static electric or magnetic fields, and more whereas the temperature field is calculated at thermal equilibrium in heat transfer. In addition, to calculate deformations, stresses, and strains in static equilibrium solid mechanics has been used.

III. RESULTS AND DISCUSSION

A stationary study with a current step of 1 mA and a simulation current range of 1 to 20 mA was chosen in accordance with the starting simulation circumstances provided. In order to simulate the temperature field distribution of the deforming process, solid mechanics stress analysis and the air medium heat transfer model were used. The temperature field distribution and stress distribution have been modeled in all scenarios because the temperature at two fixed constraint points of the model was 20 °C at the initial current.



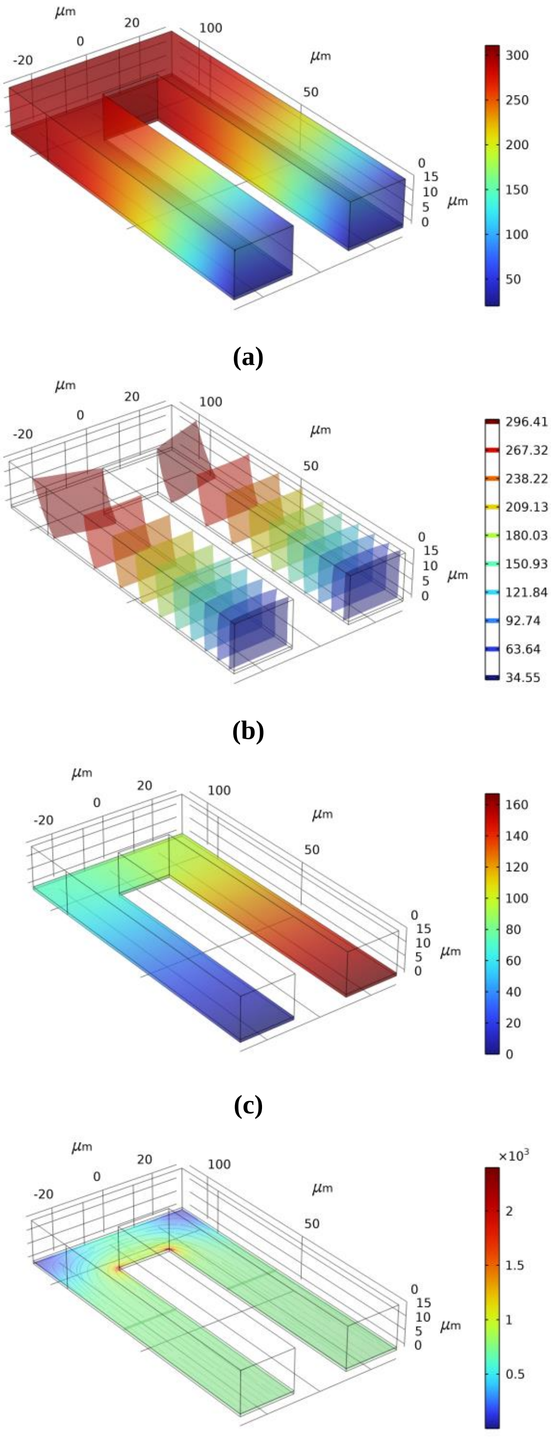
(a)

(b)

(c)

Fig. 4. (a) Bending behavior of unimorph actuator in the air environment. (b) Von Mises stress analysis of unimorph actuator during the applied current of 20 mA. (c) Strain analysis showing tension and compression of the unimorph actuator at 20 mA applied current.

In Fig. 4 the bending behavior of the unimorph actuator from the initial reference of the z-axis with the von mises stress value has been shown. For understanding, compression, and tension are also shown. In all cases, the result has been taken when the applied current is 20 mA for providing a clear view during maximum current flow. From the figure, it is clear that due to the 20 mA current nearly 5.5×10^8 Nm^2 stress has been generated which induced the bending of the actuator.



(a)

(b)

(c)

(d)

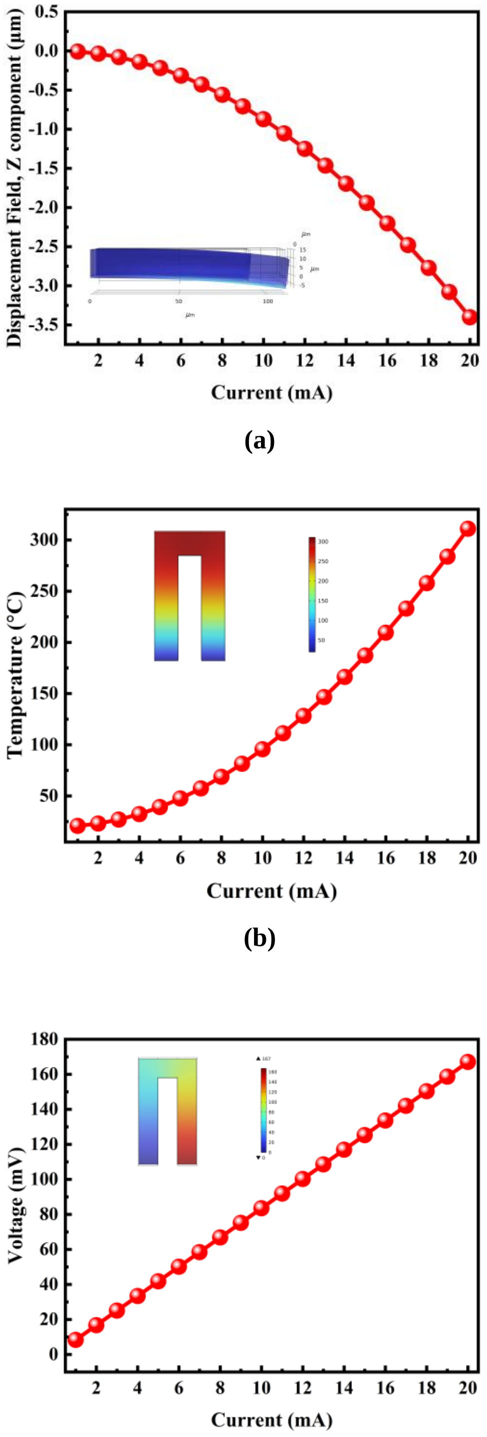
Fig. 5. (a) Temperature distribution of the unimorph actuator at 20 mA applied current. (b) Isothermal contours distribution of the unimorph actuator during the applied current of 20 mA. (c) Voltage distribution in the active layer (Ni metal) of the unimorph actuator at 20 mA applied current. (d) Electric field norm (amplitude of the electric field) distribution due to 20 mA applied current in the unimorph actuator.

Fig. 5 shows all the results when the applied current is 20 mA to better understand the device performance in the maximum applied field. In Fig. 5(a) only the temperature distribution of the unimorph actuator during the maximum applied current of 20 mA has been shown. From the figure, it is clear that the maximum temperature recorded is 300 °C in the bending area of the actuator whereas, at the boundary point, it is in low temperature like 50 °C. In Fig. 5(b) the isothermal contours distribution has been shown which fits well with the temperature distribution profile of the device. Because of the applied electric current a potential distribution has been generated throughout the surface of the metallic pad of the actuator. The voltage distribution of the actuator on the surface of the piezoelectric active layer is shown in Fig. 5(c).

From the distribution, the maximum voltage is 160 mV on the terminal side and the minimum voltage is in the ground corner. The middle of the actuator shows an average of 100 mV voltage distribution which clearly shows a uniform distribution of the voltage throughout the surface of the active layer. Fig. 5(d) shows the electric field norm distribution which also fits well with the result of the voltage distribution as the maximum electric field amplitude is 2.5×10^{3} Vm^{-1} at the critical corner of the actuator structure.

All results regarding the joule heating model have been plotted against the applied field and have been shown in Fig. 6. With the increasing current from 1 to 20 mA firstly, the displacement field of the unimorph actuator structure towards z-direction has been shown in Fig. 6(a) where the maximum displacement is 3.5 µm.

In Fig. 6(b) the temperature distribution has been plotted and in Fig. 6(c) current-voltage distribution has been plotted. All results verified the joule heating Multiphysics combining electric current-thermal heating-solid mechanics to analyze the performance using the finite element method.



(a)

(b)

(c)

Fig. 6. (a) Displacement field along Z axis versus applied current of the proposed unimorph actuator. (b) Temperature distribution along the surface versus applied current of the proposed unimorph actuator. (c) Voltage distribution in the surface versus applied current of the proposed unimorph actuator.

IV. CONCLUSION

In conclusion, a microstructure unimorph actuator has been designed and simulated for applications in MEMS-based microrobots and soft robots. The actuator reaches a maximum temperature of 300 °C at 20 mA current with a maximum voltage in the surface of 160 mV. The designed unimorph actuator has a maximum von Mises stress of 5.5×10^8 Nm^2 and the displacement during the maximum applied electric field is 3.5 µm. According to the theoretical model and simulation results, changing the effective stress in the structure can increase the actuator's displacement sensitivity and operating range. Hence, the results indicate that this structure modeling can be used in microrobots and soft robots applications. More material structure and time-dependent study analysis can be done in the future by showing a comparison between different geometrical structures.

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