Electrothermally Actuated MEMS Based Gecko Foot for Robotics

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Abstract: Gecko foots have inspired researchers to develop designs that can help robots to tread vertically oriented surface. These nanobots find many applications as they can perform a lot of operations more efficiently and also lower the cost of such operations. These can be employed in various fields: medical, industrial etc. Gecko lizards use dry adhesion van der Waals forces to climb walls produced by their spatular stalks attached on setae. The design of a 3D MEMS model of an electrothermally actuated gecko foot is presented in this paper. The working of a single microhair (with nanohairs attached to it) is discussed and the two designs, one with actuation and one without are compared.

Keywords MEMS, electrothermal actuation, Gecko adhesion, nano robotics, setae, spatular stalks.

1. Introduction

A robotic vehicle which has the capability to perform tasks on a vertical and inverted surface can dynamically automate various manual tasks increasing efficiency as well as checking the cost of operations. These can be employed in various fields such as medical, industrial and space programs.

A gecko can weigh up to 300 grams and reach lengths of 35 cm, yet is still able to run inverted and cling to smooth walls. The gecko lizards attract our interests for this purpose, their extraordinary ability to stick and run on any vertical surface has inspired researchers.
There have been many theories involving the extraordinary adhesion of the geckos. Hypotheses of glue, friction, suction, electrostatics, micro-interlocking and intermolecular forces were proposed earlier. These theories were later refuted owing to their shortcomings. The possibilities finally narrowed down to the micro-structure of the setae (microhair) on the gecko's foot. It was observed that the underside of a gecko toe typically bears a series of ridges, which are covered with uniform ranks of setae, and each setae further divides into hundreds of split ends and flat tips called spatulas (nanohair). It has been established that gecko lizards use dry adhesion forces such as van der Waals forces to climb walls [1]. By studying and imitating the attachment mechanism of this gecko, a new generation of robots can be developed making locomotion possible in almost any kind of surface without contaminating the environment.

In order to replicate this mechanism a proper design and adhesion mechanism is needed. The most common method is suction adhesion where enough vacuum is generated using pumps, so that the robot sticks against the wall. Some of its major drawbacks like time requirement of suction adhesion mechanism, or falling in case of any gaps limits the use of this mechanism. Another type of adhesion mechanism that can be implemented for specific applications involving use of a ferromagnetic surface, is magnetic adhesion [2]. It can be highly reliable in specific cases but can be employed in limited areas reducing its extensive application.

Microhair on the gecko foot is an intricate biological structure with hierarchical nanosections and microsections. A gecko has billions of nanoscale hairs on its feet that are in contact with surfaces while it climbs. In this paper we discuss a design involving the actuation of the microhairs and nanohairs which support dry adhesion and help in achieving the objective. The microhair structure is electrothermally actuated to counterbalance the reaction forces acting on it, which in turn aids the dry adhesion mechanism [3]. The same design with greater number of nanohairs is simulated without the actuation, the results has been compared and discussed.

1.1 Electrothermal Actuation

Electrothermal microactuator is made of two cantilever beams (arms) which are joined at the free end. This design produces deflection through differential heating of the two arms which are different in cross-section. Both the arms are usually made of same material. Current is circulated in the actuator structure from one anchor to another and the higher current density in the tapered beam heats it and enlarges generating an in-plane actuation about the cold arm side. When current passes through the structure, the thinner (thereby high resistant) arm heats up and expands more as compared to the thicker arm. This asymmetric expansion results in tip deflection. This design is capable of providing greater displacements in comparison to electrostatic actuators [4, 5].

The above actuation technique is used to actuate the microhair of the gecko foot. This gives an edge over the non-actuated design of the microhair. This model explores the advantages provided by electrothermal actuation by reducing the complexity in the structure.
The actuated design reduces the complexity of fabrication process which can play a key role in its practical realizations.

2. Proposed Structure

The design proposed in Fig. 1 is a standard electrothermal actuator design inspired by Ref. 3 [6]. It acts as a single microhair (setae) of the gecko foot and the nanohairs (spatula) are attached on its tip. Thus actuation of the microhair is achieved which aids the attaching and detaching mechanism of the gecko foot.

The working of this structure is also compared with the standard model given in COMSOL MEMS model library [7].

The material used is polysilicon which eases the fabrication process and also provides minimum required adhesion. Other materials like polyurethane, polyimide etc. can be used but conductivity of these materials should also be desirable [8, 9].

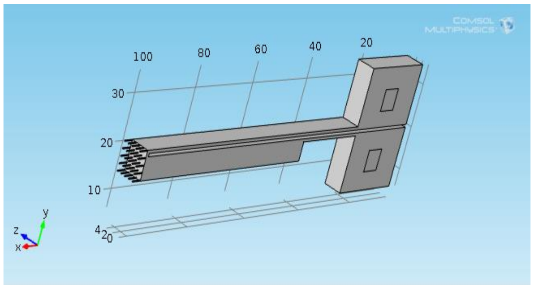

Figure 1. Proposed structure of the microhair.

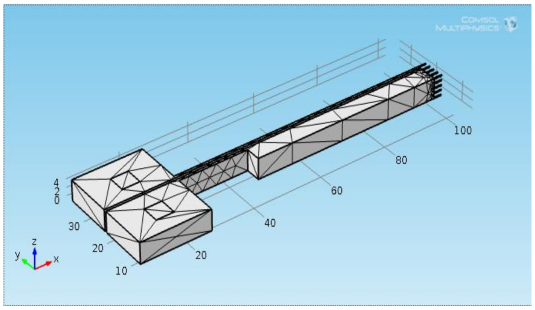

Figure 2. Finite element analysis of the structure.

3. Use of COMSOL Multiphysics

The gecko foot simulation in COMSOL Multiphysics mainly makes use of three coupled Physics namely Solid mechanics, Heat transfer in solids and Electric currents.

In FEM (finite element method) analysis continuous geometry is replaced with a set of objects with a finite number of DOF (degree of freedom) i.e. division of body into finite number of simpler units (elements) as shown in Fig. 2 [10]. Analytical methods involve solving for entire system in one operation whereas FEM involves defining the equations for each element and combining the individual results to obtain system solution. Modal analysis is the study of the dynamic properties of structures under vibrational excitation. The purpose of a modal analysis is to find the shapes and frequencies at which the structure amplifies the effect of a load. It solves an equation for which there is no applied load. It gives us specific information on the characteristics of the structure instead of reporting a response. These analysis are performed to determine the critical points of a structure and the responses under various constraints. These prove helpful in finding flaws or weakness of the structure constrained under a particular load in any direction.

It can be observed that the simulation process comprises two events, first the tip deflection due to the actuation and secondly the deflection of nanohairs attached on the tip.

Similarly, detaching can be done by removing the actuation i.e. switching off the power supply.

3.1 Equations Used

The electrothermal actuation of the structure is based on the concept of transformation of electrical energy into heat energy. The heat generated causes expansion of the structure resulting in deflection. This expansion is directly proportional to the heat generated in the material governed by thermal expansion law given by (1)

$$\Delta L = \alpha L \Delta T. \tag{1}$$

Electric potential applied to both the terminal is given by (2) which begins the actuation process.

$$-\nabla.(\sigma \cdot \nabla V_e) = 0. \tag{2}$$

The applied voltage produces a field which heats the structure except the potential terminals. The bending actions of the arms can be understood by analyzing the equations discussed below:

$$R = 1/\sigma \cdot (l/A) \tag{3}$$

$$H = I^2 \cdot R = V^2 / R \tag{4}$$

where, R is the resistance, L is the length, A is the cross-sectional area of the arm, H is the heat dissipated in Joules in the arm and I is the current flowing through the arm, σ is the conductivity. It is evident from equation (3) that resistance R is inversely proportional to the cross sectional area. It can be observed that the narrow arm will be more resistant. As a result more heat will be dissipated in the narrow arm. Also according to Joule heating and thermal expansion principles, the expansion of the arms is directly proportional to the amount of heat dissipated. This causes the narrow arm to bend pushing forward the wider arm, causing displacement.

The equation for Joule's law is given by:

$$Q = \sigma \left| \nabla V_e \right|. \tag{5}$$

The steady-state energy equation with a resistive heating source can be presented as:

$$\Delta(K \cdot \Delta T) + E^2/rho = 0 \tag{6}$$

Where *K*, *E*, *rho* and Δ*T* are thermal conductivity coefficient, electric field, electric resistivity and temperature difference respectively.

The Equation for heat transfer in solids and thermal energy exchange is stated below by (7) and (8).

$$\rho \cdot Cp \cdot u \cdot \Delta T = \nabla(K \cdot \Delta T) + Q \tag{7}$$

$$-\nabla(k(T) \cdot \Delta T) = \sigma(T) \cdot \left| \nabla V^2 \right| \tag{8}$$

C_p is the heat capacity at constant pressure, ρ is the density of the material, Q is the heat flux, T is the temperature, K is the thermal conductivity, σ is the electrical conductivity and V is the applied voltage. The above equations justify the change in the orientation of the underlying material particles which ultimately results in the requisite displacement.

The simulation in the COMSOL software concerns several steps in order to receive an actuation from applied potential which are governed by aforementioned equations.

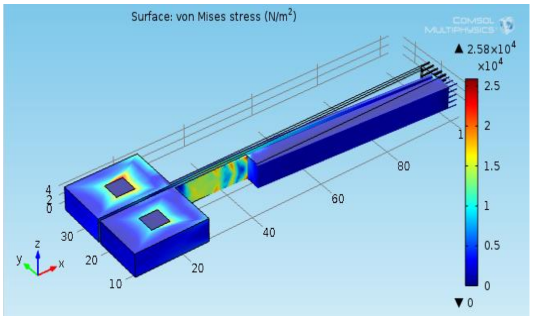

Figure 3. Stress Analysis Result.

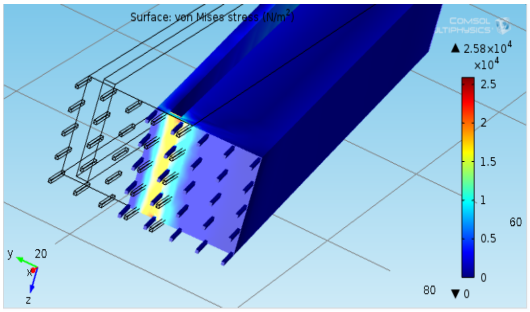

Figure 4. Nanohair displacement.

4. Result and Discussion

The working of both the structures is observed with and without actuation. In Fig. 3, the von Mises stress has been depicted when subjected to an actuation voltage. The results have been tabulated below:

Contact force = 0.4 N/Area; Friction force = 0.2 N/Area, where Area = Area of Spatula.

	Stress (N/m^2)	Max Deflection (μm)	Max Strain
Without Actuation	1.08e6	0.293	8.85e-3
With Actuation	5.85e5	7.2e-3	6.87e-7

Fig. 4 shows the nanohair displacement and the stress gradient near the tip of the microhair. It is evident from the results that both the structures have achieved the requisite objective. The point of discussion is which structure is more advantageous.

The modal analysis of the structure which is crucial in analyzing the dynamic response when subjected to varying frequencies has also been performed. Here the Eigen modes were observed for six different frequencies. The Simulation results of the deflected structure are in the form of 3D modal shapes. These indicate the responses of the structure when no load is applied. The modal shapes of the response corresponding to the Eigen modes is shown in Figs. 5 to 8.

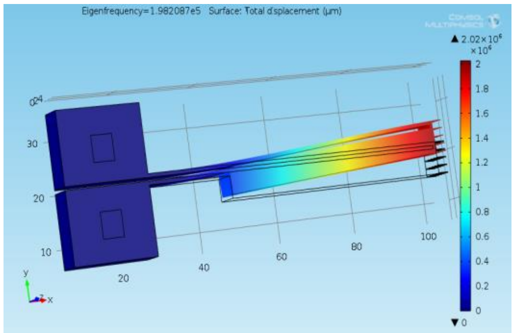

Figure 5. Mode 1

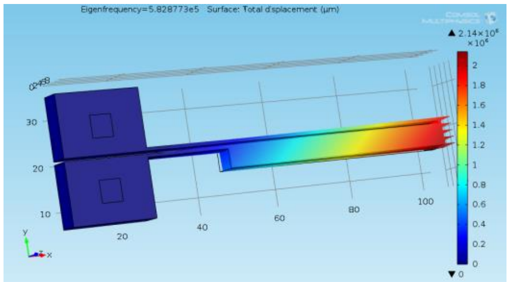

Figure 6. Mode 2

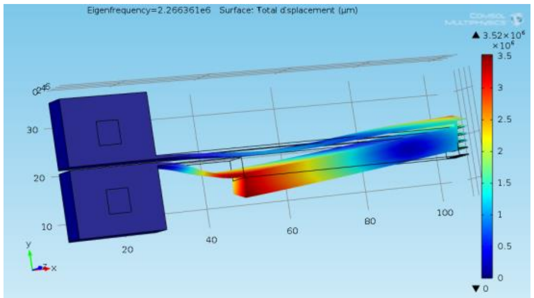

Figure 7. Mode 4

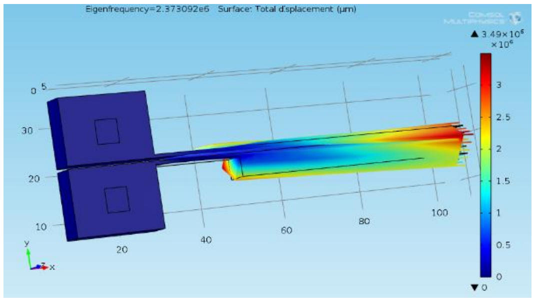

Figure 8. Mode 5

5. CONCLUSION

Based on the obtained simulation results we conclude that the actuation model has a superior performance compared to non-actuation model. This results in the requirement of a reduced number of nanohairs which cuts back the structural complexity. This reduction in the structural complexity leads to the simplification of the fabrication process manifold.

There is scope for implementation of other types of actuation schemes to this model. The structure efficiency can be further enhanced by selectively using different materials for different components. Once the device is fabricated and implemented in real time scenarios, more drawbacks will come into picture which can be easily taken care of by slight alterations in the model design.

6. References

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