A Novel Soft Robot Based on Organic Materials: Finite Element Simulation and Precise Control

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Abstract. Considering the inherent safety and high flexibility, soft robot is drawing extensive attention from both industry and academics. Soft robots made of organic materials show the merits of considerably low cost and ease of fabrication. But, the precise control of soft robot is still of great challenge. A sophisticated understanding of the motion mechanics of organic soft robot is essential for accurate control of this type of robot. In this paper, PDMS/PEDOT:PSS system, which is developed for soft robot, is modelled and simulated using finite element method. Through parameters tuning, the dependences of PDMS/PEDOT:PSS system deformation on layer thicknesses and electrical current are acquired and compared with the experimental results available in reference. Furthermore, we proposed a three layer structure for soft robot, and investigated the relationship between deformation of this structure and layer thicknesses. Our work proposed an approach for precise control for soft robot through a combination of finite element simulation and experiment data. Additionally, the three layer structure we proposed is demonstrated to be a promising solution for high response speed soft robot.

Keywords: Soft robot · PEDOT:PSS · PDMS · Finite element simulation

1 Introduction

With the promotion of mechanical engineering, automation technology and the introduction of internet, robot is ready to change the whole industry, especially in the developing countries, thoroughly. The safety and robustness of robots have been the challenging issues along the robot history. The massive application of robot requires effective solution to these issues.

Soft robot, due to its inherent characteristic, provides a promising solution to the issues of safety and robustness. The relatively low Young's modulus of the soft materials ensures that human body can be avoided from hurt once in contact with such kind of robot. On the other hand, the high resilience of soft materials employed in soft robot can protect the robot from lots of possible damages. Therefore, because of its outstanding merits, soft robot has witnessed a soaring rise in the past decade.

Y. Huang et al. (Eds.): ICIRA 2017, Part I, LNAI 10462, pp. 103–109, 2017.
DOI: 10.1007/978-3-319-65289-4_10

At the beginning, pneumatic actuation was the most prevalent driving approach for soft robot [1]. Currently, almost all the available commercial soft robots are actuated through tuning of air pressure [2]. But, the control of pneumatic actuation could be considerably rough; so soft robot based on pneumatic driving method is not suitable for tasks requires high precision. Numerous effort has been devoted to search for alternative actuation methods that meet accurate control requirement.

Organic materials, whose deformation can be controlled by electric voltage or current, can provide a route to accurate motion control for soft robot. Piezoelectric ceramics are such a type of materials. But most ceramics are extremely stiff. What's more, the deformation of piezoelectric ceramics is extremely tiny, which is too small to be competent for practical task. Then, researchers all over the world have been attempting to develop organic system that respond to voltage and current changes. So far, there are two feasible routes towards the goal: one is thermal expansion, the other one is liquid absorption and desorption.

Soft robot based on hybrid system with CNT, graphene and polymers are extensively investigated for thermal expansion actuation [3]. The small magnitude of thermal expansion leads to a limited motion range of the soft robot. On the contrary, hybrid system with a hydrophilic layer and a hydrophobic layer showed significant deformation under varied humidity. This humidity sensible hybrid system works with the hydrophilic layer absorb or desorb water under different environment [3]. Silvia Taccola et al. further improved this actuation approach by introducing electric current heating into the system [3]. They used PEDOT:PSS (poly (3, 4-ethylenedioxythiophene): poly (styrenesulfonate))/PDMS (polydimethylsiloxane) as the two layer system. PEDOT:PSS is not only hydrophilic, but also conductive. When electric current go through PEDOT:PSS layer, the hydrophilic layer is heated, water get away from it, and subsequently, it shrinks. Through this system, deformation angle as large as 360° was achieved. This actuation method enables the soft robot to complete tasks requires large motion magnitude. But its accurate control still calls for a full understanding of the fundamental mechanics during its deformation.

In this paper, with the purpose of clarifying the working mechanism of the humidity sensible soft robot, we choose the PEDOT:PSS/PDMS system as an example and investigate it with finite element simulations conducted in COMSOL. The structure parameters and voltage are changed in the simulation so as to elucidate the deformation response to the controllable variables. The temperature distribution in PEDOT:PSS/PDMS double layers through the deformation process is studied as well. In order to enhance the response speed of the system, we propose a three layer (sandwich) structure and demonstrate the feasibility of such a novel structure through finite element simulations.

2 Modelling and Simulation

The PDMS/PEDOT:PSS system is composed of two layers: one hydrophilic layer and another hydrophobic layer. The hydrophilic layer, PEDOT:PSS, can absorb water in moist environment, and desorb water under dry condition. Thence its volume will change according to the environment humidity. Meanwhile, the hydrophobic layer, PDMS, will keep its volume constant when humidity changes. As a result, the two layer structure will roll towards the PEDOT:PSS side in dry condition and towards PDMS side in wet condition, respectively. PEDOT:PSS, which is conductive as well, can heat when electric current go through it. Subsequently, water will evaporate from PEDOT:PSS layer. Then the structure will roll towards PEDOT:PSS side. Therefore, deformation of this system can be controlled by voltage. Since the water absorption and desorption processes under joule heating is alike to that of thermal expansion. To be exact, it should be thermal shrink. Considering the complexity of water absorption and desorption processes, we simplify the system by replacing the processes with thermal shrink of PEDOT:PSS layer.

The geometry of the investigated system is shown in Fig. 1. The structure parameters are set according to the actual device fabricated in the reference [3]. And initial thickness values for PDMS and PEDOT:PSS are set to be 100 μm and 0.6 μm, which are in line with the experimental data. Voltage is applied between the two gold electrodes, as indicated in Fig. 1. Considering the high coupling between the solid mechanics field, electric field and temperature field in the studied system, we adopted COMSOL Multiphysics to perform the simulation work. So as to save simulation time, the mesh size is set to be ‘normal’ in COMSOL.

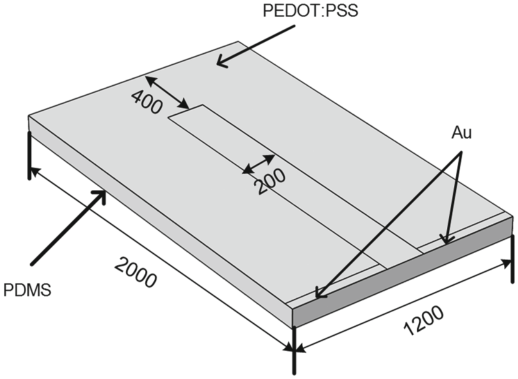

Fig. 1. Geometry structure of the the layer system studied. (Thickness of PEDOT:PSS is relatively small compared with that of PDMS)

Major parameters adopted in the finite element simulation are presented in Table 1. First of all, simulation with all parameters fixed is conducted. Then, we change the applied voltage between 0.2 and 2.4 V, with an interval of 0.2 V. And simulations with the thicknesses of PDMS and PEDOT:PSS layers varied are conducted so as to clarify the dependence of deformation on the device structure. Finally, we build up model for the sandwich structure (the three layers structure), and perform simulation to demonstrate whether it works.

Table 1. Major parameters adopted in the finite element simulation.

Parameters	Value	Units
Coefficient of thermal expansion of PDMS	3e−4 [4]	1/K
Equivalent thermal expansion coefficient of PEDOT:PSS	−1e−3	1/K
Heat capacity of PDMS	1460	J/(kg K)
Heat capacity of PEDOT:PSS	1980 [5]	J/(kg K)
Thermal conductivity of PDMS	0.15 [3]	W/(m K)
Thermal conductivity of PEDOT:PSS	0.2 [6]	W/(m K)
Poisson's ratio of PEDOT:PSS	0.34 [7]	1

3 Results and Discussions

In this paper, we attempted to study the deformation process of PEDOT:PSS/PDMS based soft robot through finite element simulation. Using the hydrophilic and hydrophobic double layer structure, the deformation of the structure upon applied external voltage is mimicked. As shown in Fig. 2, the deformation field, temperature field and the potential field in the system are acquired through the simulations simultaneously. The device is observed to deform largely towards the PEDOT:PSS layer with current go through it. And a comparison between Figs. 2(b.2) and 1(b.3) indicates that the temperature at the back of PDMS layer is significantly lower than the temperature in the PEDOT:PSS layer. This can be nicely explained by the considerably low thermal conductivity of the thick PDMS layer. The temperature is of reasonable value after heating by the circuit. Since Joule heat is generated in the PEDOT:PSS layer and the thermal conductivity of PDMS is low, the simulation results goes well with the fundamental principle. As presented in Fig. 2(c.2), the potential decreasing is symmetrical in the two arm of PEDOT:PSS structure.

The dependence of deformation and temperature on applied voltage is presented in Fig. 3. The result indicates that the deformation magnitude and temperature both increase with the voltage. As the voltage increases, the electrical current increases; then the circuit in PEDOT:PSS will generate more energy, which means higher temperature. Higher temperature will lead to more water desorbed from PEDOT:PSS. Then larger deformation is expected.

Figure 4 gives the dependence of deformation on the thickness of PEDOT:PSS. From the simulation data, we can see that deformation increases almost linear with thickness of PEDOT:PSS layer. This can be explained by the relatively thin PEDOT:PSS layer. And the resistance of the circuit will decrease linearly with the layer thickness; then the generated heat will increase linearly. Therefore, the deformation distribution is expected to increase linearly with thickness of PEDOT:PSS layer.

The three layer structure (PEDOT:PSS/PDMS/PEDOT:PSS) is modeled in COMSOL and simulated. By applying different voltage at both the PEDOT:PSS layers, the deformation field, as well as temperature and potential fields are shown in Fig. 5. The simulation demonstrates that the structure can deform towards both sides by tuning the applied voltage on both sides. Thus, the proposed structure will be a solution to the low response speed of this type of soft robot. Furthermore, it enables the structure to deform towards both sides by controlling the applied voltage in the two PEDOT:PSS layers.

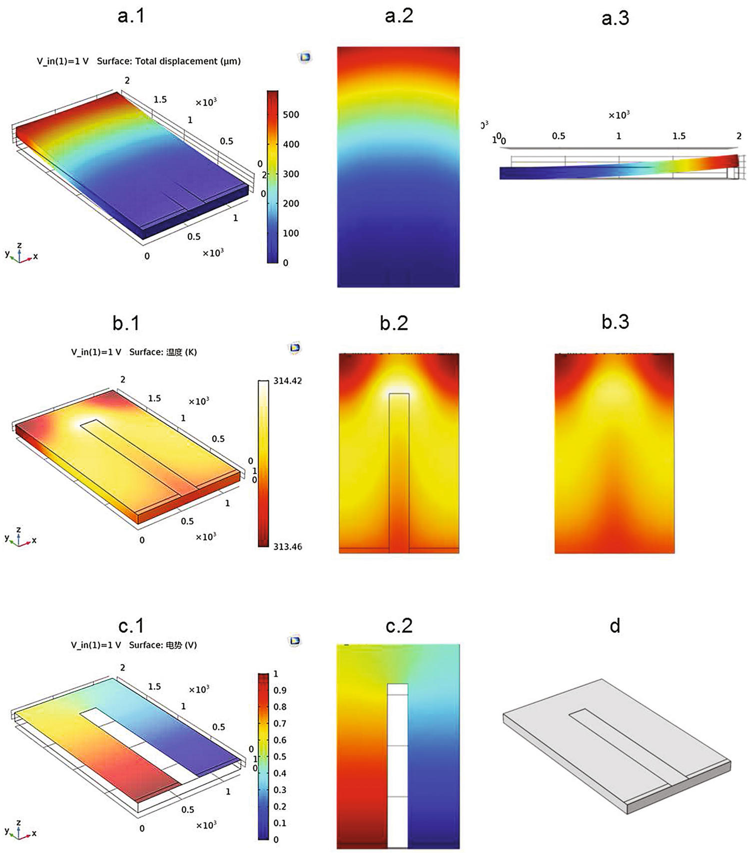

Fig. 2. Finite element simulation results with applied voltage of 1 V under 25 °C. (a.1–a.2) the deformation distribution observed at xyz-view (a.1), xy-view (a.2) and yz-view (a.3). (b.1–b.3) the temperature distribution simulation result. (b.2) and (b.3) present the temperature distribution at both the front and back sides of the device. (c.1) and (c.2) shows the potenitial distribution on the PEDOT:PSS surface.

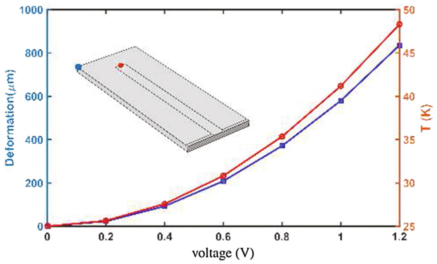

Fig. 3. The dependence of deformation and temperature on applied voltage between the Au electrodes. The deformation data is acquired at the point indicated by the blue circle; while the temperature data is acquired at the red point. The applied voltage changes from 0 V to 1.2 V, with an interval of 0.2 V.

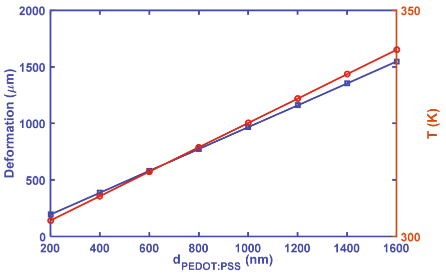

Fig. 4. The dependence of deformation and temperature on thickness of PEDOT:PSS layer. Deformation and temperature data is acquired at the points indicated in Fig. 3.

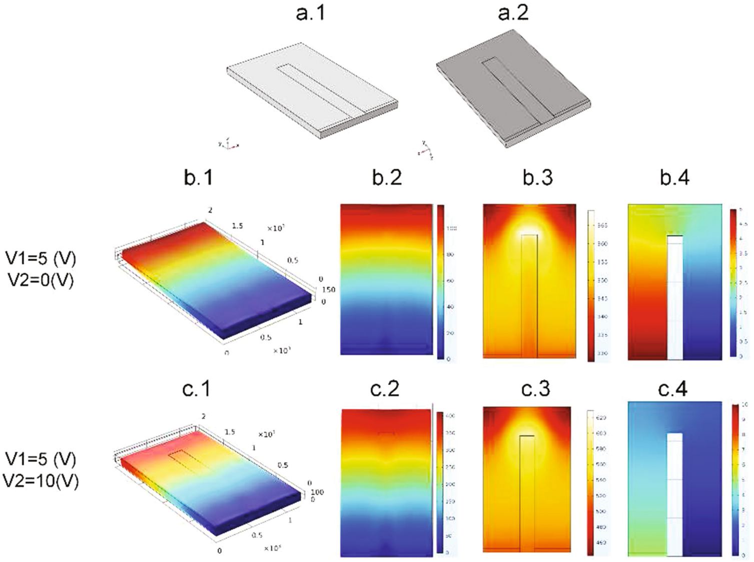

Fig. 5. Finite element simulation results for the sandwich structure (PEDOT:PSS/PDMS/PEDOT:PSS). (a) presents the geometry structure from forward and rear viewpoints. (b) displays the simulation results corresponding to $V_1 = 5$ (V) and $V_2 = 0$. (c) shows the results corresponding to $V_1 = 5$ (V) and $V_2 = 10$ (V). From left to right, the sub figures for the field distribution are deformation field at xyz view and xy view; temperature distribution and surface potential distribution.

4 Conclusions

To be concluded, in this paper, we modelled and simulated the deformation process upon electrical current exerted in the PEDOT:PSS layer in the organic soft robot. Through simulation work, we clarified the dependence of deformation on the thickness of PEDOT:PSS layer and the applied voltage. The simulation results indicate that we can figure out the exact transfer function from voltage and geometry parameters to the soft robot motion. Finally, simulation of the proposed three layer structure verified it as a possible solution to the low response speed of soft robot.

Acknowledgement. The authors need to thank the Science and Technology Department of Fujian Province, China for the funding (No. 2017J01748).

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