Review of the Manufacturing and Modeling Processes of a Soft Dielectric Electroactive Polymer Actuator

JAKUB KOŁOTA, Poznan University of Technology, Institute of Automatic Control and Robotics, POLAND

Soft robotics is an emerging discipline that combines classical robotics principles with soft materials and can provide a new class of actuators. Such equipment can support human-robot interaction facilitated by flexible and lightweight structures. Dielectric Electroactive Polymers (DEAP) are classified in the subclass of soft smart materials and are increasingly used in many automation and robotics systems. They are able to respond mechanically to an electrical stimulus or to store electrical energy from a mechanical deformation in the same way as a deformable capacitor. This makes these materials very interesting to be used as both actuators and deformation-detecting sensors. This article begins by defining how an DEAP actuator is manufactured and then goes into detail about the model definition. This study uses and discusses the technique of accurate modeling of this material, which takes into account its nonlinearity and its large deformation. The paper also presents the validation experimental results of the actuator response to the voltage excitation signal.

CCS Concepts: • **Computing methodologies** → Modeling and simulation; • **Computer systems organization** → Robotics.

Additional Key Words and Phrases: Dielectric electroactive polymer actuator, DEAP

ACM Reference Format:
Jakub Kołota. 2022. Review of the Manufacturing and Modeling Processes of a Soft Dielectric Electroactive Polymer Actuator. In *CHI'22: Actuated Materials and Soft Robotics Strategies for Human Computer Interaction Design, April 30 - May 06, 2022, New Orleans, LA.* ACM, New York, NY, USA, 6 pages. https://doi.org/XXXXXXX.XXXXXXX

1 INTRODUCTION

A polymer membrane is required to produce a soft dielectric actuator. Various solutions can be used, however, one should have fundamental material parameters, such as: dielectric constant, material stiffness, and viscoelasticity [1]. The dielectric constant is related to Maxwell stresses, therefore it has an influence on the amount of deformation of the actuator. The significant viscoelasticity of the membrane in turn lowers the actuator performance. The most commonly used materials are acrylic elastomers and silicones. Both solutions have their advantages and disadvantages. Elastomers are characterized by high dielectric constants, however, they have high viscoelasticity. Silicones, on the other hand, are less viscoelastic, but have lower dielectric constants and are characterized by lower Young's modulus (silicone Wacker Elastosil RT 625 is $0.303MPa$, silicone Nusil CF19-2186 is $1.0MPa$ while acrylic 3M VHB 4910 is $3.0MPa$) [12]. In this paper, the author presents the actuator made of 3M™ VHB™ 4910 tape, while in another author's work [6] you can learn about the ways of producing an actuator with a silicone membrane. The principle of operation of DEAP actuators built with the use of an elastomer tape has been presented in detail in the works [6][11][10]. The Figure 1 and Figure 2 show graphically how the actuator membrane stretches as a result of the applied voltage.

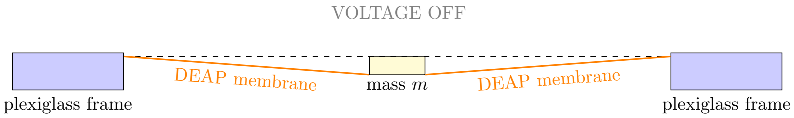


Fig. 1. Diagram of DEAP actuator with power off

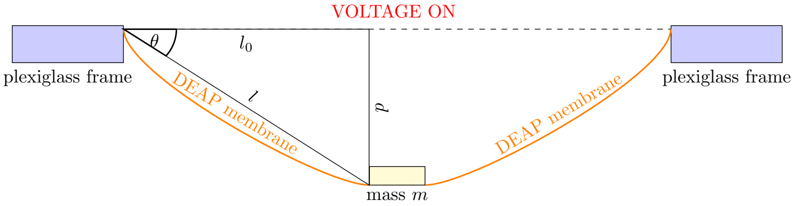


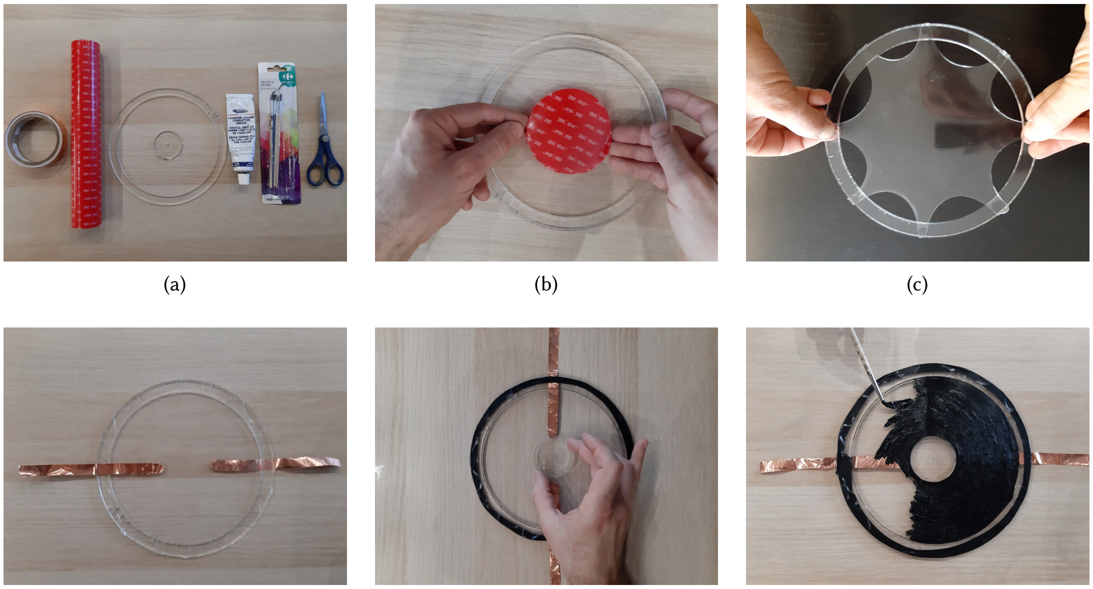
Fig. 2. Diagram of DEAP actuator with power on

2 DESCRIPTION OF THE DEAP ACTUATOR MANUFACTURING PROCESS.

The DEAP actuator works with a polymer membrane that is prestretched (red roll in Figure 3a). Therefore, to prepare the membrane for sticking, it is first necessary to calculate the initial prestretch diameter (Figure 3b). The study assumes that the membrane is stretched to a thickness of 180 μm. Table 1 shows all actuator dimensions, where r is the radius of the weight lying in the center of the membrane, marked as an additional mass in the Figure 1 and Figure 2.

Before applying the membrane on the plexiglass, make sure that the surfaces are dry and free of condensed moisture. It is best to prepare the frame by cleaning it with a 50:50 mixture of isopropyl alcohol and water. Then, symmetrically stretch the membrane and stick it carefully to the actuator frame (Figure 3c). Good surface contact can be attained by applying enough pressure to ensure that the tape experiences approximately 15 psi (100 kPa). Note that a rigid plexiglass frame of DEAP requires 2 or 3 times that much pressure to make the tape experience 15 psi. It is important information that the elastomers membranes age and are sensitive to the environment parameters, which affects the performance of the actuator. The author has experienced damage to an actuator that has been exposed to sunlight for several hours. All 3M™ VHB™ tapes have a shelf life of 24 months from the date of manufacture when stored at 40°F to 100°F (4°C to 38°C) and 0-95% relative humidity. The optimum storage conditions are 72°F (22°C) and 50% relative humidity. After application, the bond strength will increase as the adhesive flows onto the plexiglass surface. At room temperature, approximately 50% of ultimate bond strength will be achieved after 20 minutes, 90% after 24 hours and 100% after 72 hours [9].

After sticking the stretched membrane, we can proceed to the preparation of the power connectors for connecting the voltage to the membrane. First, cut and then glue the strips of copper tape. They should reach about half of the radius of the membrane and adhere well to it. For this purpose, commonly available copper tape was used (Figure 3d). At this stage, we also stick the plexiglass disc to the membrane, which will create an additional load on the actuator (Figure 3e). The next step is to apply the electrodes (Figure 3f). The author used carbon grease 846 MG Chemicals. It is a smooth creamy grease for lubricating and improving electrical connections between moving parts. The paste is ideal for flexible electrodes because it has reliable performance, a wide operating temperature range, and is relatively cheap. The actuator prepared in this way can be tested and supplied with high voltage to identify its dynamic parameters. Due to the high voltage operation, it is very important to be particularly careful when operating the actuator.



(a) (b) (c)

(d) (e) (f)

Fig. 3. DEAP actuator manufacturing process: starter kit (a), cut membrane before stretching (b), stretching the actuator membrane (c), sticking the electrodes (d), sticking the central disc (e), painting the electrodes with carbon paste (f).

Table 1. Dimensions of the DEAP actuators

Parameters	Symbol	Value	Unit
Prestrech tape diameter	-	94	mm
Prestrech tape diameter	-	210	mm
Membrane initial thickness	-	1	mm
Membrane final thickness	z_0	0.18	mm
Internal plate radius	r	25	mm
External plate outer diameter	-	210	mm
External plate inner diameter	-	180	mm
Electrode width	l_0	65	mm

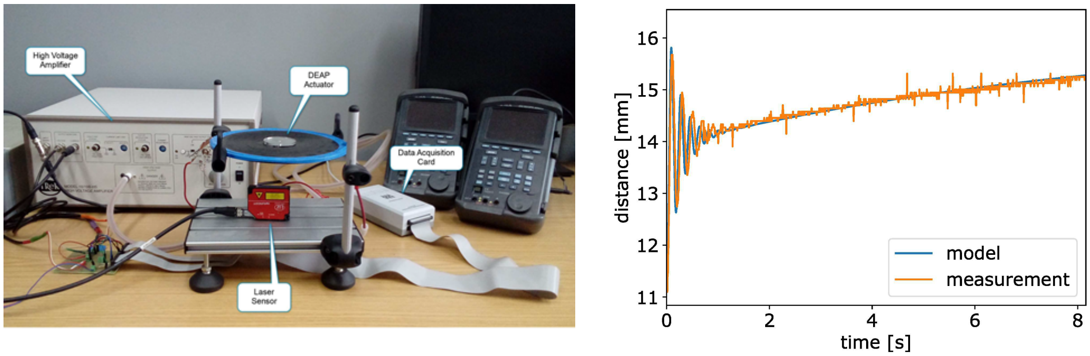
3 NONLINEAR MODEL OF DEAP ACTUATOR

There are many works that describe different modeling methods and analytical models [8][13][14]. In this study, the model described in the works [11][2][10] was used, in which the deflection of the DEA membrane is described by the radial stretch λ_r, circumferential stretch λ_c and thickness stretch λ_z.

$$\lambda_r \lambda_z \lambda_c = 1, \ \lambda_r = \frac{l}{l_0} = \frac{\sqrt{l_0^2 + d^2}}{l_0}, \ \lambda_z = \frac{z}{z_0}, \ \lambda_c = const \tag{1}$$

where :

$$z = z_0 \frac{l_0}{l} = z_0 \frac{l_0}{\sqrt{l_0^2 + d^2}}, \; sin(\theta) = \frac{d}{\sqrt{l_0^2 + d^2}} \tag{2}$$



(a) (b)

Fig. 4. The laboratory kit with DEAP actuator (a) and the distance response for a step voltage signal (b).

The vertical force equilibrium causing membrane deformation can be defined as the dynamic relationship between the input voltage u and the output actuator displacement d:

$$m\ddot{d} = mg + F_L - sin(\theta)(F_M + F_h + F_f) \tag{3}$$

where θ is an angle, m is the mass of the initial load, g means standard gravity and F_L defines the external load. The value of F_M which defines Maxwell force is equal to:

$$F_M sin(\theta) = \overline{c_1} c_2 d u^2 \tag{4}$$

and

$$\overline{c_1} = \frac{2\pi r z_0}{l_0} \; c_2 = -\frac{\varepsilon_0 \varepsilon_r}{z_0^2} \tag{5}$$

where ϵ_0 is the vacuum permittivity and ϵ_r is the relative permittivity. Force F_h considers a dynamic viscoelastic process according to:

$$F_h sin(\theta) = \overline{c_1} d \sigma_e \left(\frac{l_0^2}{l_0^2 + d^2} \right) \tag{6}$$

$$\sigma_e = -k_e \epsilon_e + k_e(\lambda_r - 1) + \underline{\sigma_e} \;\; \text{where} \;\; \dot{\epsilon_e} = -\frac{k_e}{\eta_e}\epsilon_e + \frac{k_e}{\eta_e}(\lambda_r - 1) \tag{7}$$

where k_e and η_e are parameters that define the level of viscoelasticity of the membrane. There are many hyperelastic strain energy density functions, such as Yeoh, Ogden, Arruda-Boyce, etc. Similar to [11], the author used the Ogden model and defined two parameters β_i and γ_i to obtain the expression for the hyperelastic stress:

$$\underline{\sigma_e} = \sum_{i=1}^{3} \left(\beta_i \lambda_r^{\alpha i} - \gamma_i \lambda_r^{-\alpha i} \right) \tag{8}$$

where α_i is 2, 4, and 6. Finally, the viscous friction force F_f dependent on the damping factor b was defined as:

$$F_f sin(\theta) = b\dot{\lambda_r} sin(\theta) \tag{9}$$

4 EXPERIMENTS

The experiments concerned the identification of the model and verification of the correctness of the actuator model in correlation with the real device. The laboratory set presented in Figure 4a contained a high voltage amplifier TREK MODEL 10/10B-HS and laser distance sensor Micro-Epsilon optoNCDT ILD1320-10 with 1 μm accuracy. The input signals were generated with the use of a PC computer with RT-DAC/USB2 card, which is a multifunction input/output board dedicated to real-time data acquisition and control.

At the beginning, the static characteristics were analysed. Set of unknown parameters of the Odgen model (γ_i and β_i) have an influence on the static behavior of the DEAP actuator material and therefore were identified first to change the distance without applied voltage [2]. Next, the steady state characteristic under voltage excitation was used to determine the relative permittivity. Providing a 6 kV voltage signal enabled to obtain a step response presented in the Figure 4b, which was used to determine coefficients of viscoelasticity k_e, η_e and damping coefficient b. The procedure for obtaining the values of all identified parameters has been described in detail in the work [2]. The faithful model of the actuator obtained in this way allowed the author to further verify the control methods [5][3][4][7].

5 CONCLUSIONS

Intelligent soft materials are a new trend in automation and robotics. This work shows how an dielectric electroactive polymer actuator can be manufactured and tested in a homemade way. Manufacturing multiple materials today makes it possible to embed different components in soft robotics to improve the integration of functionality. Having the knowledge of how DEAP actuators work, we can try to improve them and develop them in the direction of improving the efficiency and possibilities of their applications. The present and future works of the author are related to the attempt to produce a new type of electrodes for the DEAP actuator and optimization of the force generated by the actuator using permanent magnets and magnetorheological elastomers (MRE) techniques.

ACKNOWLEDGMENTS

Funding: This research was funded by Ministry of Education and Science, grant number 0211/SIGR/6434 and was realized within the framework of project 0211/SBAD/0121 (Poznań University of Technology)

REFERENCES

[1] Yoseph Bar-Cohen. 2004. *Electroactive Polymer (EAP) Actuators as Artificial Muscles: Reality, Potential, and Challenges* (2nd. ed.). SPIE PRESS, Bellingham, Washington USA.

[2] J. Bernat and J. Kolota. 2019. Adaptive Observer for State and Load Force Estimation for Dielectric Electro-Active Polymer Actuator. *IFAC-PapersOnLine* 52, 16 (2019), 448–453. https://doi.org/10.1016/j.ifacol.2019.12.002 11th IFAC Symposium on Nonlinear Control Systems NOLCOS 2019.

[3] Jakub Bernat and Jakub Kolota. 2019. Adaptive Observer for State and Load Force Estimation for Dielectric Electro-Active Polymer Actuator **This work was realized with the frame of project SONATA 13 No. 2017/26/D/ST7/00092 from National Science Centre (Poland). *IFAC-PapersOnLine* 52, 16 (2019), 448–453. https://doi.org/10.1016/j.ifacol.2019.12.002 11th IFAC Symposium on Nonlinear Control Systems NOLCOS 2019.

[4] Jakub Bernat and Jakub Kolota. 2021. Active Disturbance Rejection Control for Dielectric Electroactive Polymer Actuator. *IEEE Access* 9 (2021), 95218–95227. https://doi.org/10.1109/ACCESS.2021.3094271

[5] Jakub Bernat and Jakub Kolota. 2021. A PI Controller with a Robust Adaptive Law for a Dielectric Electroactive Polymer Actuator. *Electronics* 10, 11 (2021). https://doi.org/10.3390/electronics10111326

[6] Jakub Bernat, Jakub Kolota, and Samuel Rosset. 2021. Identification of a Nonlinear Dielectric Elastomer Actuator Based on the Harmonic Balance Method. *IEEE/ASME Transactions on Mechatronics* 26, 5 (2021), 2664–2675. https://doi.org/10.1109/TMECH.2020.3044492

[7] Jakub Bernat and Jakub Kołota. 2021. DEAP Actuator Composed of a Soft Pneumatic Spring Bias with Pressure Signal Sensing. *Energies* 14, 4 (2021). https://doi.org/10.3390/en14041189

[8] Giovanni Berselli, Rocco Vertechy, Mitja Babič, and Vincenzo Parenti Castelli. 2013. Dynamic modeling and experimental evaluation of a constant-force dielectric elastomer actuator. *Journal of Intelligent Material Systems and Structures* 24, 6 (2013), 779–791. https://doi.org/10.1177/1045389X12457251 arXiv:https://doi.org/10.1177/1045389X12457251

[9] Technical Bulletin. 2017. *3M Surface Preparation for 3M™ VHB™ Tape Applications*. 3M. Retrieved January 22, 2022 from https://multimedia.3m.com/mws/media/66019O/vhbtm-tape-surface-preparation-technical-bulletin.pdf

[10] Jakub Kołota. 2020. The FEM Model of the Pump Made of Dielectric Electroactive Polymer Membrane. *Applied Sciences* 10, 7 (2020), 2076–3417. https://doi.org/10.3390/app10072283

[11] G. Rizzello, D. Naso, A. York, and S. Seelecke. 2015. Modeling, Identification, and Control of a Dielectric Electro-Active Polymer Positioning System. *IEEE Transactions on Control Systems Technology* 23, 2 (2015), 632–643. https://doi.org/10.1109/TCST.2014.2338356

[12] L.J. Romasanta, M.A. Lopez-Manchado, and R. Verdejo. 2015. Increasing the performance of dielectric elastomer actuators: A review from the materials perspective. *Progress in Polymer Science* 51 (2015), 188–211. https://doi.org/10.1016/j.progpolymsci.2015.08.002 Environmentally Relevant and Hybrid Polymer Materials.

[13] F. Rosenblatt, J. F. Morrison, and L. Iannucci. 2008. Modelling electroactive polymer (EAP) actuators: electro-mechanical coupling using finite element software. In *Electroactive Polymer Actuators and Devices (EAPAD) 2008*, Yoseph Bar-Cohen (Ed.), Vol. 6927. International Society for Optics and Photonics, SPIE, San Diego, California, United States, 333 – 342. https://doi.org/10.1117/12.776086

[14] J W Zhang, J W Chen, and Z Q Ren. 2020. Mechanical behavior of a circular dielectric elastomer membrane under out-of-plane deformation. *Journal of Mechanics* 37 (12 2020), 184–191. https://doi.org/10.1093/jom/ufaa026 arXiv:https://academic.oup.com/jom/article-pdf/doi/10.1093/jom/ufaa026/36349872/ufaa026.pdf