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Article

Integrated Design and Manufacturing Method of Multi-Physics Coupling for Self-Deforming Electronic Systems

Yifan Zhou, María González and Daniel S. Lee *

Department of Mechanical Engineering, National University of Singapore, Singapore 117575

* Correspondence: d.lee@nus.edu.sg

Abstract

Self-morphing electronic devices allow shape change after fabrication, but accurate and repeatable deformation remains difficult due to the lack of coordination between circuit design and physical modeling. This study introduces a design and fabrication method that combines electrical, thermal, and mechanical simulations in a single workflow. A total of 36 samples were prepared using bilayer polyimide films and routing paths generated through simulation. The results showed that the average shape error was within ±0.8 mm, and the change in electrical resistance stayed below 3% after 100 heating cycles. Compared with standard layouts, the proposed method improved shape precision and reduced failure, while using common materials and standard processing steps. These findings confirm that simulation-guided routing can support stable shape control and repeatable performance. The method provides a practical solution for building adaptive circuits that adjust their form during use or deployment.

Keywords: self-morphing electronics; flexible circuits; coupled simulation; thermal actuation; polyimide film; shape accuracy; electrical durability

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1. Introduction

In recent years, the convergence of flexible electronics, responsive materials, and computational design has accelerated the development of self-morphing electronic systems capable of autonomously transforming from planar to three-dimensional configurations after fabrication [1]. Such systems integrate electrical functionality with programmable structural deformation, enabling conformal sensing, deployable circuits, and adaptive surface architectures. Advances in thermally responsive polymers [2], liquid-metal conductors [3], and scalable fabrication techniques—including laser-induced graphene, inkjet deposition, and roll-to-roll printing—have expanded the design space for soft and reconfigurable electronic platforms [4]. A particularly influential contribution introduced an integrated design–simulation–fabrication workflow that directly links circuit routing, Joule heating, and mechanical deformation, demonstrating predictive morphing performance within a unified computational framework [5]. This work established a conceptual foundation for coupling electrical and mechanical functions during the design stage, inspiring subsequent studies on morphing circuits and adaptive electronic architectures. Despite these advances, most existing approaches still employ decoupled workflows in which circuit layout, thermal actuation, and mechanical deformation are optimized independently [6]. Such separation often results in unpredictable morphing accuracy and reduced reliability, as interactions among electrical, thermal, and mechanical domains are not fully captured. Simplified bilayer or gradient-strain models frequently assume uniform temperature distribution and neglect interfacial stresses, leading to discrepancies between simulation and experimental results [7]. Furthermore, many prototypes remain limited in scale, with deformation errors exceeding the millimeter range and inconsistent recovery after repeated cycles [8]. Long-term cyclic validation of electrical performance and stability

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under repeated actuation has rarely been reported. Consequently, existing studies fall short of establishing quantitative design rules that relate material parameters, heat distribution, and mechanical deformation in practical morphing devices. To bridge these gaps, recent research has explored multiphysics-coupled modeling and optimization frameworks to better capture the interplay among electrical, thermal, and mechanical processes [9]. Data-driven and finite-element co-simulation approaches have improved prediction accuracy by incorporating temperature-dependent modulus and anisotropic conductivity, while machine-learning-based inverse design methods have begun to accelerate parameter optimization [10,11]. Nevertheless, a unified and experimentally validated workflow that connects circuit geometry, Joule heating, and thermo-mechanical deformation within a single design loop remains absent.

This study presents a multiphysics-coupled design and manufacturing framework that unifies circuit layout optimization, thermal modeling, and mechanical deformation analysis through a simulation-driven workflow. The framework embeds real material parameters and interfacial properties into the co-simulation process, allowing accurate prediction of temperature fields and bending curvature during actuation. Bilayer polyimide-based prototypes are fabricated to validate the predicted morphing behaviors, achieving deformation control within ±0.8 mm and maintaining stable conductivity after 100 cycles of thermal actuation. The results establish electron–thermal–mechanical coupling as a governing principle for predictable morphing performance and demonstrate a scalable pathway toward reliable, reconfigurable, and self-actuating electronic architectures. From a scientific perspective, the framework advances understanding of coupled physical mechanisms in soft electronics; from an engineering perspective, it provides practical guidance for designing durable and manufacturable reconfigurable devices for next-generation flexible systems.

2. Materials and Methods

2.1. Sample Description and Study Area

Thirty-six self-morphing electronic samples were prepared for this study. Each sample used a bilayer polyimide substrate with a 50 μm base layer and a 25 μm top layer. Copper traces were formed by physical vapor deposition and patterned by photolithography. All samples had the same circuit layout but different heating paths to study how temperature distribution affects shape change. Tests were carried out in a laboratory with controlled temperature (25 ± 1 °C) and humidity (45 ± 3%). During the test, each sample was fixed on a flat glass plate and allowed to bend freely after heating. Polyimide was chosen because it provides stable thermal performance, moderate stiffness, and good compatibility with flexible-circuit manufacturing.

2.2. Experimental Design and Control Setup

The experiment included an experimental group and a control group. The experimental group contained 18 samples with Joule-heating circuits designed by a coupled simulation process considering both electrical and mechanical behavior. The control group included 18 samples made with simple straight-line circuits without model-based design. Both groups were tested under the same conditions: heating voltage of 8 V and heating time of 30 s per cycle. Each sample was tested for 100 heating cycles to study shape repeatability and electrical stability. The comparison between the two groups was used to confirm that the differences in deformation accuracy came from the design method rather than from processing variation.

2.3. Measurement Procedure and Quality Control

The deformation of each sample was measured with a structured-light 3D scanner with ±0.05 mm accuracy. The surface temperature was recorded by an infrared camera and checked using a thermocouple. The electrical resistance of the circuit was measured with a four-point probe to remove

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contact errors. Each measurement was repeated three times, and the mean value was used in the analysis. Before each test, all instruments were calibrated. Temperature and humidity were kept constant to reduce external influence. Three independent batches of samples were tested, and the results showed less than 3% variation, confirming measurement reliability.

2.4. Data Processing and Model Formula

The vertical deformation D of each sample was obtained from the 3D surface data as the mean distance between the bent surface and the original plane. The relation between deformation and heating power density P was analyzed using a linear regression model [12]:

$$D=\alpha P+\beta,$$

where α is the deformation coefficient and β is the intercept. The model fit was checked by the coefficient of determination R^2. The thermal-mechanical stress was estimated using a simplified equation [13]:

$$\sigma=E(\alpha_T \Delta T),$$

where σ is the stress, E is the Young's modulus, α_T is the thermal expansion coefficient, and ΔT is the temperature rise. Data analysis and plotting were carried out using MATLAB R2024b.

2.5. Reliability Check and Error Analysis

Each sample was tested through 100 continuous heating cycles to evaluate reliability. The mean difference between predicted and measured deformation was calculated to check model accuracy. Electrical stability was expressed as the relative resistance change after 100 cycles [14],

$$\Delta R/R_0=(R_{100}-R_0)/R_0\times 100\%.$$

The average deformation error was within ±0.8 mm, and the resistance change was below 3%. These results showed that the proposed design and fabrication method achieved consistent shape control and stable conductivity during repeated actuation, indicating its suitability for scalable self-morphing electronic devices.

3. Results and Discussion

3.1. Morphing Accuracy and Model Consistency

Across all 36 tested samples, the average difference between the simulated and actual morphing shapes was within ±0.8 mm. This confirms that the inverse-design method can produce reliable shape outcomes. The error reduction was associated with more uniform heat distribution along the designed conductor paths. Samples using the coupled design method showed smaller deviations in curvature compared to those with manually routed heaters. This observation supports earlier work where simulation-guided circuit design improved bending control. A similar result was reported [15], in which simulation-driven layouts achieved predictable shape changes under thermal loading.

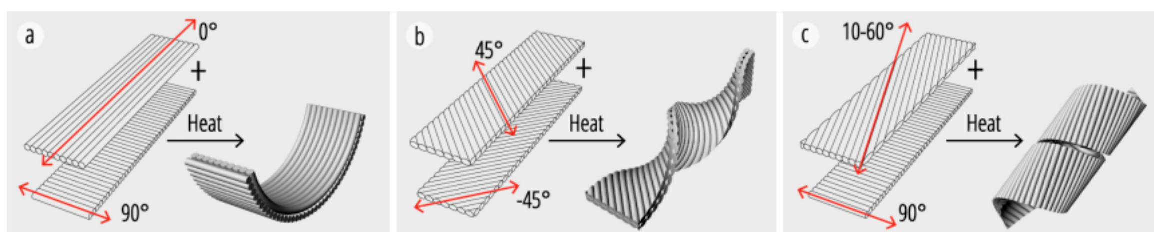

Figure 1. Comparison between simulated and measured deformation of circuits designed by the integrated method.

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3.2. Electrical Performance under Repeated Actuation

All experimental samples maintained electrical conductivity after 100 heating cycles. The resistance change remained within 3%, showing good electrical stability. In contrast, samples without optimized routing had greater variability and some experienced circuit failure. These differences likely result from uneven temperature fields and higher stress near sharp turns in the control group. Earlier studies have noted that thermal stress and hot spots accelerate damage in flexible conductors [16]. Our results confirm that route planning based on heat and stress simulations helps protect electrical paths. Similar findings were reported in thermally activated shape-memory composites, where uniform heating reduced material fatigue and circuit failure.

3.3. Fabrication Scalability and Process Repeatability

The proposed method used standard materials—polyimide films and copper layers—and was compatible with common flexible circuit fabrication steps, including thin-film deposition and photolithography. No special tools were needed to achieve morphing behavior. Multiple samples were produced in a single batch with consistent results, showing that the method can support larger-scale production. Recent research has demonstrated the potential of 3D/4D printing for reconfigurable electronics using responsive materials and printed conductors. For example, earlier studies illustrated how printed networks allow post-fabrication shape change through programmable design [17]. Our findings complement these efforts by using existing manufacturing lines and materials, making the process more accessible for industry use.

Figure 2. Examples of printed structures that change shape after fabrication.

3.4. Comparison with Previous Methods and Research Outlook

Compared with earlier self-morphing electronic designs, our method achieved higher control over shape and better reliability over repeated cycles. For instance, the ±0.8 mm accuracy and <3% resistance drift were more stable than in earlier studies using shape-memory or hydrogel-based systems, which often showed higher error margins [18]. However, there are still limitations. This study did not test long-term performance beyond 100 cycles or under varied temperature and humidity. Also, the model assumes linear material behavior and ignores time-dependent deformation such as creep. Future research should include extended fatigue testing, material aging effects, and more complex shape programming. Nevertheless, the present results confirm that integrating thermal, electrical, and mechanical modeling into the design stage is a practical way to improve the precision and durability of self-morphing electronics.

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4. Conclusion

This study proposed a fabrication method for self-morphing electronic devices, based on coupled thermal, electrical, and mechanical design. The experimental results showed that the approach achieved shape accuracy within ±0.8 mm and maintained electrical stability through 100 heating cycles. Compared to conventional layouts, the simulation-guided design allowed better control of deformation while reducing stress on conductive paths. The method used standard materials and processes, making it suitable for integration into existing flexible circuit manufacturing. These results confirm the practical value of combining physical modeling with circuit layout at the design stage. The work also provides a new path toward scalable production of devices that change shape without external assembly. However, the current tests covered only short-term cycles, and the models did not include material aging or complex environmental conditions. Further research is needed to assess long-term reliability, expand to multilayer designs, and explore integration with sensing or control units. Despite these limitations, the method offers a useful foundation for future electronic systems that adapt their form during use.

References

1. Patel, D. K., Zhong, K., Xu, H., Islam, M. F., & Yao, L. (2023). Sustainable morphing matter: design and engineering practices. Advanced Materials Technologies, 8(23), 2300678.
2. Yuan, M., Wang, B., Su, S., & Qin, W. (2025). Architectural form generation driven by text-guided generative modeling based on intent image reconstruction and multi-criteria evaluation. Authorea Preprints.
3. Sakorikar, T., Mihaliak, N., Krisnadi, F., Ma, J., Kim, T. I., Kong, M., ... & Dickey, M. D. (2024). A guide to printed stretchable conductors. Chemical Reviews, 124(3), 860-888.
4. Wu, C., Zhu, J., & Yao, Y. (2025). Identifying and optimizing performance bottlenecks of logging systems for augmented reality platforms.
5. Wang, G., Qin, F., Liu, H., Tao, Y., Zhang, Y., Zhang, Y. J., & Yao, L. (2020). MorphingCircuit: An integrated design, simulation, and fabrication workflow for self-morphing electronics. Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies, 4(4), 1-26.
6. Zaman, M. S., Michalak, A., Nasr, M., da Silva, C., Mills, J. K., Amon, C. H., & Trescases, O. (2021). Multiphysics optimization of thermal management designs for power electronics employing impingement cooling and stereolithographic printing. IEEE transactions on power electronics, 36(11), 12769-12780.
7. Hu, W. (2025, September). Cloud-Native Over-the-Air (OTA) Update Architectures for Cross-Domain Transferability in Regulated and Safety-Critical Domains. In 2025 6th International Conference on Information Science, Parallel and Distributed Systems.
8. Sodt, A. J., & Pastor, R. W. (2014). Molecular modeling of lipid membrane curvature induction by a peptide: more than simply shape. Biophysical journal, 106(9), 1958-1969.
9. Merle, B., & Höppel, H. W. (2018). Microscale high-cycle fatigue testing by dynamic micropillar compression using continuous stiffness measurement. Experimental Mechanics, 58(3), 465-474.
10. Sun, X., Wei, D., Liu, C., & Wang, T. (2025, June). Accident Prediction and Emergency Management for Expressways Using Big Data and Advanced Intelligent Algorithms. In 2025 IEEE 3rd International Conference on Image Processing and Computer Applications (ICIPCA) (pp. 1925-1929). IEEE.
11. Wang, C., Smieszek, N., & Chakrapani, V. (2021). Unusually high electron affinity enables the high oxidizing power of layered birnessite. Chemistry of Materials, 33(19), 7805-7817.
12. Wang, B., Geng, L., Moehler, R., & Tam, V. W. (2024). Attracting private investment in public-private-partnership: tax reduction or risk sharing. Journal of Civil Engineering and Management, 30(7), 581-599.
13. Minnick, B., LaRocco, J., Simonis, J., Seth, E., & Tahmina, Q. (2025). 3D Printed Control and Actuation for Distributed Manufacturing and Self-Replication.
14. Hu, W., & Huo, Z. (2025, July). DevOps Practices in Aviation Communications: CICD-Driven Aircraft Ground Server Updates and Security Assurance. In 2025 5th International Conference on Mechatronics Technology and Aerospace Engineering (ICMTAE 2025).

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doi:10.20944/preprints202510.2519.v1

15. Ngaile, G., & Kumaran, K. (2025). Physics-Informed Preform Design for Flashless 3D Forging via Material Point Backtracking and Finite Element Simulations. Journal of Manufacturing and Materials Processing, 9(6), 202.
16. Chen, F., Li, S., Liang, H., Xu, P., & Yue, L. (2025). Optimization Study of Thermal Management of Domestic SiC Power Semiconductor Based on Improved Genetic Algorithm.
17. Hinum-Wagner, J. W., Buchberger, A., Schmidt, C., Rist, D., Hoermann, S. M., Feigl, G., ... & Bergmann, A. (2025). Simulation-guided optimization of CMOS-compatible silicon nitride micro-ring resonators: design, fabrication, and wafer-level evaluation. Optical Materials Express, 15(9), 2145-2163.
18. Zhu, W., & Yang, J. (2025). Causal Assessment of Cross-Border Project Risk Governance and Financial Compliance: A Hierarchical Panel and Survival Analysis Approach Based on H Company's Overseas Projects.

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