nature portfolio

Peer Review File

Field-Programmable Robotic Folding Sheet

Corresponding Author: Professor Jung Kim

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
This manuscript presents a strategy to fabricate and control robotic sheets that could deform via localized folding to achieve in-situ reprogramming. The folding stems from electrothermally induced mismatch in thermal expansion of a bilayer structure. The robotic sheet incorporates a distributed set of networked metallic resistors, serving both to heat the robotic sheet and monitor the local temperature. A resistive network imaging (RNI) scheme is used to investigate the electrical potential distribution by recruitment of electrode pairs for current injection and voltage measurement, thereby reconstructing the temperature field based on the resistance-temperature relationship. The center temperature measured is then mapped to the bending curvature of the locally created hinge. A closed-loop PI temperature control method is employed to achieve spatiotemporal control of the grasping and locomotion capabilities.

Overall, this work offers an interesting perspective to realize reprogramming of smart material structures without physical intervention, and the proposed RNI scheme addresses the challenge of measuring and reconstructing the temperature distribution inside of the structure. However, the reviewer has doubts about the practical values of this technology, given the complexity of the fabrication, the structure and the manoeuvring.

First, hardware-wise, the authors soldered ultrathin electrical wires to the resistor network for electrode connection. How is the wiring and routing done inside and outside of the robotic sheet? Is a wire connected to each circular junction of the resistors? (In fact, in Extended data Fig. 1, there are large and small circular junctions.) Does the resistive heating from the electrical wires contribute to the temperature distribution? How to mitigate the mechanical interference caused by the large number of wires during operation of the robotic sheet?

Second, according to the manuscript and the supplementary notes, the resistive network comprises 308 transistors and requires 1470 voltage measurements for the addressable actuation and RNI process of a 7x7 grid arrangement. Additionally, the electronic transfer within a resistive network could be more complicated than what is considered in this work. For example, the junctions and the weld spots could very well contribute to altering the spatial distribution of the electrical resistance. These aspects would make the already tedious process less reliable.

Third, the aforementioned issues would lead to the problem of scalability of the technology. The number of resistors, measurements and numerical iterations would all multiply if the sample is scaled up or the resolution is increased. Moreover, the influences of the sheet thickness as well as the convection heat transfer conditions could become more significant for larger scales.

(Remarks on code availability)

Reviewer #2

(Remarks to the Author)
This paper presents a field-programmable "robotic sheet" featuring a very elaborate network of resistors and electrodes embedded in responsive material layers. Such a high-resolution resistor network can function as a thermal actuator and sensor, enabling on-demand, programmable folding with closed-loop feedback. The authors demonstrated the use of such robotic folding sheets via simple manipulation and locomotion tasks.

Overall, I found this work fascinating. The high resolution of thermal actuators/sensors is unprecedented in sheet-like morphing materials. More importantly, the seamlessly integrated closed-loop feedback control on folding presents a breakthrough in origami engineering. Therefore, this paper is an excellent fit for publication in Nature Communication.

The authors can further improve the paper by addressing some fundamental questions I have in mind.

Complexity of fold lines (folding pattern):
Origami folding is a great motivation for this study, and the authors demonstrated that their robotic sheets could show mountain and valley folds at different locations and different orientations. However, all these fold lines are simple, straight lines, and they do not intersect with each other. If we look at classical origami design (e.g., Miura-Ori, Water bomb base), a key feature is that their mount-valley fold lines will join at a point (aka., degree 4 or 6 vertexes), thus creating elaborate shapes. For the robotic sheet in this study, would it be possible to develop these kinds of complex folding shapes by patterning mountain valley folds and allowing vertices to form? More broadly, what kind of folding is possible beyond isolated bending?

Feedback control:
The feedback control on robotic folding is a commendable accomplishment. Would the authors give a more *quantitative* assessment of the control performance (from the angle of a robotics control engineer)? For example, what is the steady-state error between the targeted and actual folding angles? (PI controller, in principle, should give zero steady-state error, but that depends on the accuracy of the sensing). How much disturbance can the controller reject? Can a high proportional control gain help reduce the setting time, thus making the folding faster? (slow folding is always the Achilles heel of thermal-induced origami folding).

Load bearing capacity and Functionality?
Based on the robotic demonstration, the loading-bearing capacity seems relatively low. The targeted objects are all pretty lightweight. Therefore, I am unsure whether object lifting is the best use of this new robotic sheet. Could the authors explore other possible uses to better exemplify the advantage of such on-demand and closed-loop controlled folding/morphing?

(Remarks on code availability)

Reviewer #3

(Remarks to the Author)
Shape-morphing structures, especially those inspired by origami and folding, are an emerging frontier in mathematics, computer science, and robotics. They enable devices to adapt their shape for different tasks or environments, providing embodied intelligence and versatility. Field-Programmable Robotic Folding Sheet addresses this frontier by presenting a thin robotic sheet that can be programmed after deployment to fold into various configurations on demand. This capability, termed “field-programmability,” is a significant advancement over traditional foldable robots with fixed hinges or predetermined fold patterns. The manuscript under review is highly relevant to the field, as it combines innovations in materials, actuation, and control to achieve reconfigurable 3D shapes from a 2D sheet. In the following, I outline the key strengths of this work, suggest minor improvements, and conclude with a strong recommendation for acceptance.

Strengths
1. Demonstrated Programmability of the Folding Sheet
The paper convincingly demonstrates that the robotic sheet’s folding pattern is fully programmable in situ. The same sheet can assume an unbounded set of hinge configurations post-deployment, meaning the location, direction, and angle of folds can be chosen and reprogrammed on the fly. This level of programmability is unprecedented—previous folding robots typically had fixed crease lines or could only cycle through a limited set of pre-designed shapes. Here, by contrast, the authors show the sheet forming diverse shapes (from basic bends and waves to more complex multi-fold geometries) all through electronic commands. This proves the concept of a single physical device being able to realize many structural forms, essentially treating shape as a software-controlled variable. The ability to reconfigure the folding profile repeatedly and reversibly in the field is a remarkable contribution to adaptive robotics.

2. Novel Use of Electrothermal Actuation for Shape Morphing
A core innovation is the sheet’s embedded electrothermal actuation system. The authors integrate a dense network of metallic resistive elements within a thermo-responsive polymer layer, creating “pixels” that can be individually heated. This is a novel application of electrothermal actuators in a distributed, sheet-like format. By Joule heating selected regions, the polymer folds along those lines; when heating is removed, it cools and can flatten back, enabling bidirectional (reversible) folding.

Importantly, each resistor not only acts as a heater but also as a sensor (thermistor), allowing the sheet to sense its own temperature distribution. This dual functionality enables a built-in feedback mechanism—often referred to as resistive network sensing—that the authors use for closed-loop control of the folding process. The electrothermal approach is shown to be fast, producing folds quickly, and strong enough to achieve large bending angles (on the order of ±90°). Unlike pneumatic or magnetic actuators used in other shape-morphing systems, this electronic heating method is self-contained (requiring no external fields or bulky equipment) and easily integrated with onboard electronics. The result is a robust and elegantly simple means of morphing the sheet's shape with fine spatial addressability.

4. Expanding Programmable Matter through a New Methodology
This work introduces a new methodology for programmable matter, where a material system's physical configuration is programmable by the user. By blending materials (responsive polymer), hardware (embedded resistor network), and software (control algorithms for addressing and feedback), the authors create a sheet that behaves like a reconfigurable matter module.

The field-programmable folding strategy means the sheet's geometry is no longer fixed at manufacture—it can evolve and adapt on demand. This is analogous to how field-programmable gate arrays (FPGAs) allow circuits to be reprogrammed dynamically; here, the authors introduce a field-programmable mechanical structure. Such reconfigurability vastly expands the design space for shape-changing devices.

5. Potential Applications in Robotics, Autonomous Systems, and Materials Science
The manuscript does an excellent job of not only developing the technology but also illustrating its real-world applications. The authors present two compelling demonstrations:

Reconfigurable Robotic Gripper: The sheet is programmed to switch between multiple grasping modes (wrapping, pinching, multi-fingered hold) all within a single device. This adaptability allows for handling diverse object shapes with a gentle, conformal grip.
Shape-Shifting Locomotion Platform: The sheet crawls, walks, and waves across surfaces, mimicking bio-inspired movements such as inchworm crawling and rolling locomotion. Its recorded locomotion speeds (5–25 mm per cycle) showcase its potential as an untethered mobile robot.
Beyond these examples, autonomous shape-adaptive exploratory robots and deployable structures could leverage this technology, opening pathways for applications in space exploration, biomedical engineering, and soft robotics.

Minor Suggestions for Improvement
While this manuscript is already exceptionally strong, a few minor refinements could further enhance its impact:

1. Clarification of Universality: While the authors demonstrate the programmability of the sheet, a short explanation of how the box-pleated structure mathematically enables universal 3D shape formation (possibly with a simple diagram) would help clarify this crucial contribution.

A possible suggestion is to explain the integration of Box-Pleated Patterns for Universal 3D Shape Construction. For example:
An important mathematical foundation of this work is the incorporation of a box-pleated pattern into the robotic sheet's folding design. The box-pleated origami pattern has been mathematically proven to be universal, meaning that by appropriately arranging its folds, it can approximate any 3D shape that can be represented as a voxel-based model. This universality allows the robotic sheet to mimic arbitrary 3D geometries, providing a level of adaptability that extends beyond conventional origami-based shape morphing.

The robotic sheet uses a box-pleated origami pattern—a regular grid of creases with alternating diagonals—that enables it to fold into many tiny box-like segments. In simple terms, this means the sheet can partition itself into small cube-shaped units (voxels) by choosing certain creases to fold while leaving others flat. Mathematically, it has been proven that this type of crease pattern (tetrakis tiling) is universal, meaning that by adjusting its folds, it can represent any shape composed of unit cubes joined face-to-face. By using a fine enough grid, the sheet can approximate virtually any 3D form with arbitrary accuracy. Unlike custom fold patterns that must be designed for each shape, the box-pleat pattern provides a general-purpose mold that can realize a broad library of shapes simply by reprogramming fold activations.

This property has profound practical implications for robotics, adaptive structures, and programmable materials. A single field-programmable sheet can be instructed to morph into a multitude of structures or tools on demand. For instance, the same sheet might fold into a manipulatory gripper, then flatten and refold into a rolling wheel or deployable shelter, all without requiring reassembly. This shape-shifting material effectively acts like a reconfigurable "display" for 3D objects, where different geometries emerge based on selected fold sequences. The ability to generate any shape defined by a voxel-based model suggests a direct link between computational geometry and physical morphing, further strengthening the paper's contributions to the fields of robotics, materials science, and applied mathematics.

2. Discussion on System Limitations: It would be beneficial to explicitly discuss practical constraints, such as durability over repeated cycles and energy efficiency. This could provide insights into long-term deployment scenarios and scalability for larger structures.
These suggestions do not detract from the paper's excellence but are intended to make its contributions even clearer to a broad readership.

Conclusion and Recommendation
In summary, Field-Programmable Robotic Folding Sheet is an outstanding contribution that significantly advances reconfigurable robotics and smart materials. The authors introduce a new paradigm for dynamic shape programming, leveraging electrothermal actuation and computationally controlled folding. This work will be of great interest to researchers across robotics, materials science, and programmable matter.

I strongly recommend acceptance of this manuscript, as it meets the highest standards of scientific rigor, innovation, and relevance.

(Remarks on code availability)

Reviewer #4

(Remarks to the Author)
I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

(Remarks on code availability)

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
The authors have satisfactorily responded to my concerns. I am happy to recommend that the revised manuscript be published in its present form.

(Remarks on code availability)

Reviewer #2

(Remarks to the Author)
The authors have addressed my comments well with additional experiments and clarifications. This is a great study to start with, and the revision makes it even better. Thus, I recommend publication at Nature Communications.

(Remarks on code availability)

Reviewer #3

(Remarks to the Author)
Final Review Memo

Overall assessment
The authors have substantially strengthened the theoretical foundations of the work. In particular, the clearer explanation of the box-pleat pattern's universality - supported by classic references - now anchors the experimental results in a solid mathematical context. The first submission already demonstrated impressive experimental rigor; with these additions, the manuscript is even more compelling. I therefore maintain my recommendation of "Strongly Accept".

Reference correction
Please replace the current citation for Reference 49 (an arXiv version) with the formally published source below:
Demaine, E., Tachi, T., Uehara, R. et al. "Universal Hinge Patterns to Fold Orthogonal Shapes," in Origami 5: Proceedings of the 5th International Conference on Origami in Science, Mathematics and Education (OSME 2010), Singapore, July 13-17 2010, A K Peters, pp. 405-420.

Optional additional reading
For those interested in further work on box-pleat origami and single-sheet self-folding, the following papers may be useful. They are offered purely for background; there is no need to cite them in the manuscript.

An, B. et al. "Planning to Fold Multiple Objects from a Single Self-Folding Sheet," Robotica 29 (1): 87–102 (2011).
Hawkes, E. et al. "Programmable Matter by Folding," PNAS 107 (28): 12441–12445 (2010).
An, B. & Rus, D. "Designing and Programming Self-Folding Sheets," Robotics and Autonomous Systems 62 (7): 976–1001 (2014).

Conclusion
The added theoretical discussion and supplementary experiments elevate an already strong contribution. With the minor reference update noted above, the manuscript is ready for publication.

(Remarks on code availability)

[Response to Reviewers' Comments]

Reviewer #1

[General review]

This manuscript presents a strategy to fabricate and control robotic sheets that could deform via localized folding to achieve in-situ reprogramming. The folding stems from electrothermally induced mismatch in thermal expansion of a bilayer structure. The robotic sheet incorporates a distributed set of networked metallic resistors, serving both to heat the robotic sheet and monitor the local temperature. A resistive network imaging (RNI) scheme is used to investigate the electrical potential distribution by recruitment of electrode pairs for current injection and voltage measurement, thereby reconstructing the temperature field based on the resistance-temperature relationship. The center temperature measured is then mapped to the bending curvature of the locally created hinge. A closed-loop PI temperature control method is employed to achieve spatiotemporal control of the grasping and locomotion capabilities.

Overall, this work offers an interesting perspective to realize reprogramming of smart material structures without physical intervention, and the proposed RNI scheme addresses the challenge of measuring and reconstructing the temperature distribution inside of the structure. However, the reviewer has doubts about the practical values of this technology, given the complexity of the fabrication, the structure and the maneuvering.

[Our response]

We appreciate your thorough review of our manuscript and critical comments that help improve the quality of our manuscript. We would like to answer to your comments in point-by-point, including the practical values of this technology.

[Comment #1]

First, hardware-wise, the authors soldered ultrathin electrical wires to the resistor network for electrode connection. How is the wiring and routing done inside and outside of the robotic sheet? Is a wire connected to each circular junction of the resistors? (In fact, in Extended data Fig. 1, there are large and small circular junctions.) Does the resistive heating from the electrical wires contribute to the temperature distribution? How to mitigate the mechanical interference caused by the large number of wires during operation of the robotic sheet?

[Our response]

Since this comment raises three concerns at once, we subdivided our response as follows.

1) The method for wiring and routing

Firstly, we would like to provide additional explanations regarding our solder pad formation process. The actual wire connection is made at a large circular junction (d = 2 mm), where an external wire is soldered onto the pad that is fabricated during the solder pad formation process (see Supplementary Fig. 6d–i, k). In contrast, the small circular junction (d = 0.4 mm) is part of the resistive network, designed as a crossover point among resistors. The circular design was intended to prevent undesirable current concentration. We included the details about the role of each junction in the caption of Supplementary Fig. 2 as follows:

In Supplementary Information, Supplementary Fig. 2

Before:

Supplementary Fig. 2. Description of the networked resistor. a-c, Photograph of the networked resistor imaged by an optical camera (**a, b**) and microscope (**c**). Scale bars: 9 mm (**a**), 2 mm (**b**), 100 μm (**c**).

After:

Supplementary Fig. 2. Description of the networked resistor. a-c, Photograph of the networked resistor imaged by an optical camera (**a, b**) and microscope (**c**). The actual wire connection is made at a large circular junction (d = 2 mm), where the small circular junction (d = 0.4 mm) is part of the resistive network, designed as a crossover point among resistors. Scale bars: 9 mm (**a**), 2 mm (**b**), 100 μm (**c**).

2) Whether the electrical wires contribute to the temperature distribution or not

Our wire-based interconnection does not contribute significantly to thermal energy regulation due to its substantially lower resistance compared to the resistors in the sheet. Specifically, the electrical wire and its contact point to the sheet have a resistance of approximately 2.5 Ω, whereas our resistor network exhibits an electrode-to-electrode resistance on the order of hundreds of ohms (a single adjacent resistor in the sheet shows approximately 600 Ω). Since thermal energy increase is directly proportional to the square of the resistance, it is reasonable to conclude that the contribution of the electrical wires is negligible. This claim is supported by a temperature imaging measurement, as shown in **Figure R1**.

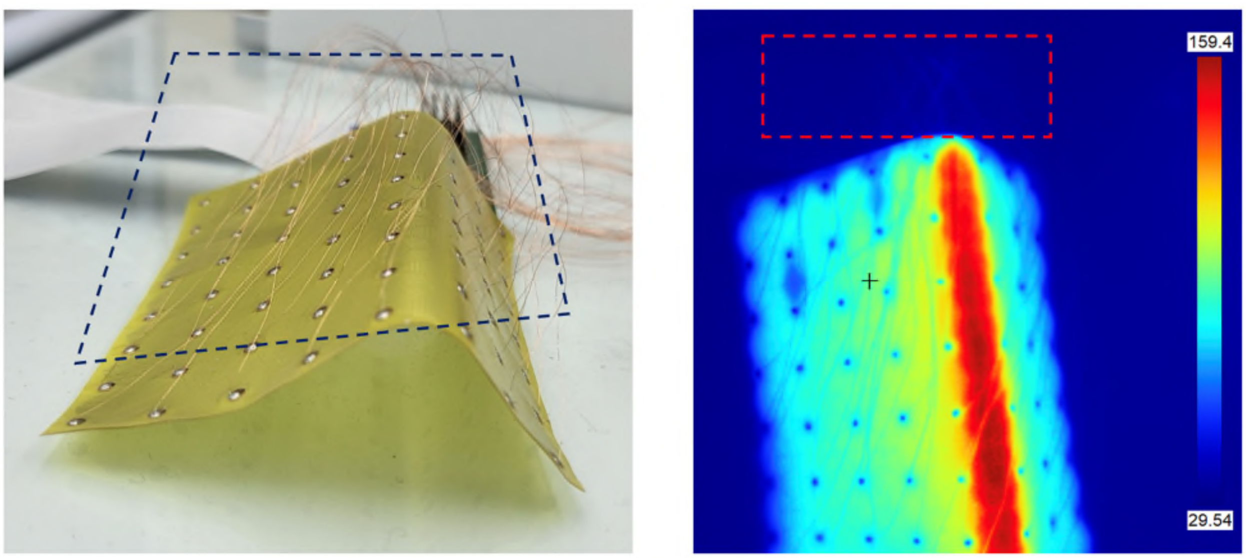


Figure R1. Example confirming the effect of wire heating (For response letter only). As shown in the right figure, within the red dotted rectangle, the temperature of the wires is similar to the ambient temperature, confirming that the wires were not heated during the heating of the field-programmable robotic sheet at its maximum temperature.

3) Regarding the mechanical interference caused by the wires

Our tethered system design is indeed one of the key drawbacks. To maximally reduce such concern, ultra-thin wires are adopted (diameter of 50 μm), and we observed the minimal mechanical influence during our demonstration experiments. With alternative methods, the wiring can be removed through different system designs. For instance, in our on-going work, we replaced it with the patterned routes on the double-sided flexible PCB, as shown in **Figure R2**. The resulting hardware can be operated through simply plugging into a connector. Despite our alternative, the reason that we chose to use the ultra-thin wires at current work is to present maximized degree of freedom in programmability of shape (the clamped region for the PCB connection loses its shape-morphing capability). We included the discussion on such limitations and future directions to the main text as follows:

In Manuscript, Discussion (Highlight in concerning part):

Before:

... grasping and locomotion. Future improvements in these capabilities include geometrically scalable material designs (including metamaterials), intrinsic shape sensing, digital twinning toward data-efficient computation, and wireless drives, expanding the scope of versatile engineering methodologies by blending intelligence in morphology and computation.

After:

... grasping and locomotion.

Despite these promising features, several concerns should be addressed to further mature our technology. First, the mechanical performance should be improved to enhance both shape responsiveness and load-bearing capacity. Additional material advancements should be investigated beyond our micro-rod structure, including thermo-responsive meta-materials that outperform conventional materials[55], or a structural design with a thicker form factor that would require accelerated cooling mechanisms[56, 57]. Such modifications would enable more complex folding process featuring overlapping or curved folds. Second, the practical applications of the robotic sheet should be explored in greater depth, including potential demonstrations as a light modulator[47] or a dexterous robotic platform for environmental monitoring[58]. To this end, the replacement of wire-based interconnections to in-hardware electrode traces and the straightforward insertion of add-on elements, such as intrinsic shape sensing modalities, should be further investigated. Furthermore, the demonstration of generalized shape programmability with various form factors would extend the effectiveness of our framework that would incorporate the flexible assembly of unit elements across scales and dimensions. All these breakthroughs would expand the scope of versatile engineering methodologies by blending intelligence in morphology and computation.

In Manuscript, Reference:

Newly Included:

55. Ni, X., Guo, X., Li, J., Huang, Y., Zhang, Y., Rogers, J. A. 2D Mechanical Metamaterials with Widely Tunable Unusual Modes of Thermal Expansion. *Advanced Materials* **31**, 1905405 (2019).

56. Liu, Y., *et al.* Fully inkjet-printed Ag_2Se flexible thermoelectric devices for sustainable power generation. *Nat Commun* **15**, 2141 (2024).

57. Kim, S., Lee, S., Lee, J. *et al.* Passive isothermal film with self-switchable radiative cooling-driven water sorption layer for arid climate applications. *Nat Commun* **15**, 8000 (2024).

58. Kumar, V. *et al.* Microengineered Materials with Self-Healing Features for Soft Robotics. *Adv Intell Syst* **3**, 2100005 (2021)

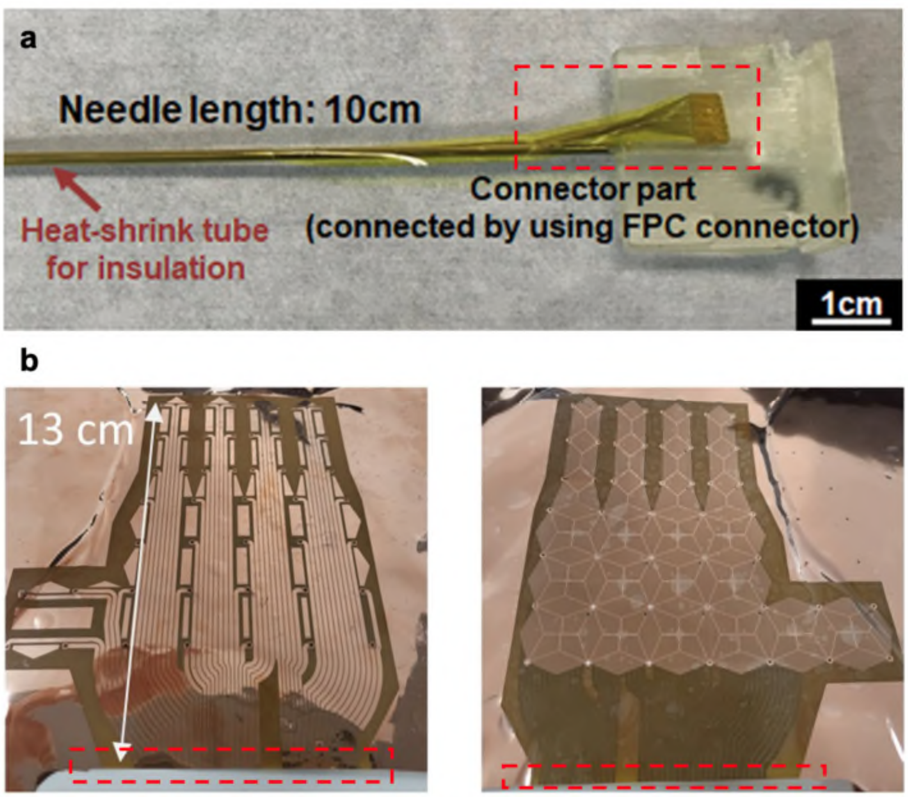


Figure R2. Example of the flexible printed circuit (FPC) cable-based electrode configuration (For response letter only). **a,** Conventional examples of fabricating FPC cable-integrated electronics [*ACS Sens*. **5**, 1363-1373 (2020)]. **b,** An example of applying this strategy to our system. The end, highlighted by the red dot box, is designed to be plugged into FPC connectors.

[Comment #2]

Second, according to the manuscript and the supplementary notes, the resistive network comprises 308 transistors and requires 1470 voltage measurements for the addressable actuation and RNI process of a 7x7 grid arrangement. Additionally, the electronic transfer within a resistive network could be more complicated than what is considered in this work. For example, the junctions and the weld spots could very well contribute to altering the spatial distribution of the electrical resistance. These aspects would make the already tedious process less reliable.

[Our response]

The electronical operation for our RNI process involves current stimulation and voltage measurement by using pair electrodes for each. In such pair electrode selection, the electronic transfer follows the pathway of wire/via hole/resistive network/via hole/wire, where the via hole is composed of the junctions and weld spots. The resulting electrical effect from the rest of resistive network would be governed by their resistance, which we would call as the side resistance (sum of the resistances of wire, via hole and contact resistance between resistive network and the via hole). In other words, the less reliability in our FEM-simulation-based RNI method would be derived from the undesirably high side resistance.

However, our careful design on the resistive network suppresses the effect. First of all, we imposed a sufficiently high resistance value to each networked resistor, to over than 500 Ω, through precise tuning of geometrical parameters (width and thickness of the serpentine pattern) in the micropatterns. Meanwhile, the solder wetting layer was carefully optimized, in terms of soler paste type (SAC305), solder paste amount (controlled by pressure of dispenser (5 atm) and dispensing time (0.3 s)) and soldering condition (250 ℃ of hot plate, 10 s), to lead the robust connection with overall side resistance as ≤ 5 Ω.

Since the side resistance value is hard to be precisely controlled in practice, we performed an additional simulation study to supplement our claim (**Figure R3**). Without loss of generality, the side resistance is modeled as a serial resistance heading from each electrode, which is of common approaches when regarding contact impedance for generic electronic operations. Given that configuration, it was observed that the current range of side resistance displays no noticeable influence on the RNI performance (≤ 2 % of mean average percentage error in the voltage measurements).

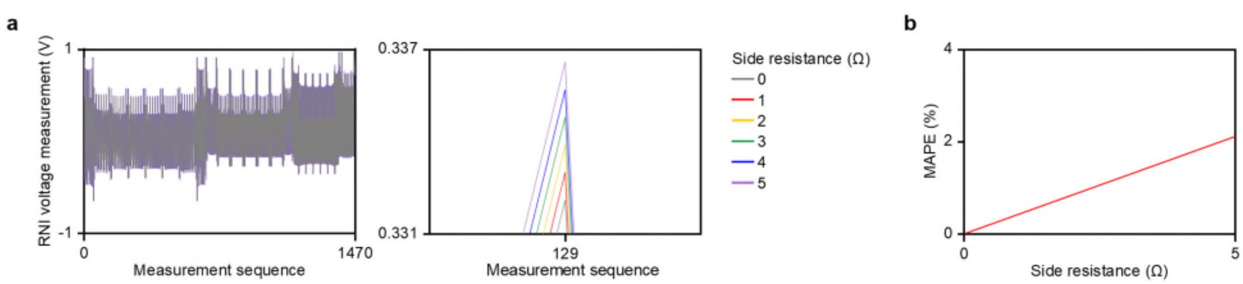


Figure R3. Simulation study on the effect of side resistance on Resistive Network Imaging (RNI) (For response letter only). **a**, Raw voltage measurements across selected side resistance values. **b**, Mean average percentage error (MAPE) of the voltage measurements across the side resistance range of 0 – 5 Ω.

[Comment #3]

Third, the aforementioned issues would lead to the problem of scalability of the technology. The number of resistors, measurements and numerical iterations would all multiply if the sample is scaled up or the resolution is increased. Moreover, the influences of the sheet thickness as well as the convection heat transfer conditions could become more significant for larger scales.

[Our response]

As the reviewer mentioned, the scalability is a key specification for maturation of our technology. Following the comment, the scalability can be discussed in terms of two aspects: spatial resolution, and form factors.

1) Spatial resolution

A higher degree of freedom in the shape-programming process is desired to achieve richer shape programmability. This goal primarily depends on the density of electrodes. It is true and inevitable that increasing the number of electrodes necessitates many considerations in hardware, measurement, and computation. However, such advancement would not present a significant bottleneck, because many high-density addressing schemes, exemplified by OLED devices and optical metasurfaces, have recently shown great promise in addressing all the aforementioned aspects.

Despite these achievements, implementing dense elements would remain challenging for large-scale actuation applications like ours. The limitations are attributed to the mechanical durability, particularly the ability to withstand intensive out-of-plane deformation, and limits in current smart actuation energy densities. Therefore, we respectfully insist that our networked design approach can present one feasible alternative, because the method can further enrich the degree of freedom under the same electrodal configuration (in other words, the one can reduce the density of electrodes while maintaining the level of degree of freedom, making the hardware design more straightforward). We have thoroughly investigated this enrichment in terms of singular value analysis for distribution control. To further support our claim, we have newly included an analysis of distributional variance, as follows:

In Manuscript, Methods, Functional Basis.:

Before:

...configurations (example cases of comparison are shown in Supplementary Fig. 11).

After:

...configurations (example cases of comparison are shown in Supplementary Fig. 22). A distributional variance analysis further supports the outperformance of the networked domain (see Supplementary Note 6 and Supplementary Fig. 23).

In Supplementary Information:

Newly included:

Supplementary Note 6: Distributional variance analysis

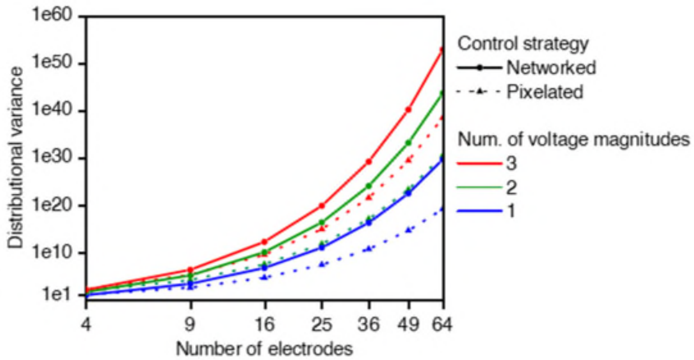
The proposed network-based control method is designed as a promising candidate for the conventional pixelation approaches. A comparative quantitative analysis on the effectiveness of the network method was performed by investigating possible variance of the output distribution. Given n number of grid electrodes that are regularly distributed in a square domain, thereby having a square number, and k number of nonzero voltage magnitudes imposed to the electrodes, both methods have $(2k+1)^n$ cases in voltage distribution, when accounting for the directionality in the voltage values. The number of unique power distributions for the point control method ($\mathcal{N}_{pixel}$) is computed as

$$\mathcal{N}_{pixel}(n,k) = (k+1)^n \,. \tag{S4}$$

In case of the network-based method, there exist multiple voltage configurations that result in an identical power distribution. As the simplest instance, any set of voltage configurations consisting of two discrete values can share the same power distribution with configurations in which those values are interchanged or uniformly shifted. The duplication can occur upto $2(2k+1)$ times, depending on the network structure and the shape of output. Therefore, there exists a lower bound on the distributional variance of the network control $\mathcal{N}_{network}$, which can be expressed using big- Ω notation as

$$\mathcal{N}_{network}(n,k) = \Omega\left\{\frac{(2k+1)^n}{2(2k+1)}\right\} = \Omega\left\{\frac{(2k+1)^{n-1}}{2}\right\}. \tag{S5}$$

We note that this approach is a conservative setting that facilitates the intuitive characterization by avoiding the highly complex calculation on the exact number of cases. Supplementary Fig. 23 depicts the result of the distribution variance according to the range of n and k. The network control method displays its outperformance in terms of the variability in configuring power distribution compared to the pixelation.



Supplementary Fig. 23. Distributional variance analysis of the resistor network. The number of possible unique power distributions is theoretically computed with respect to the number of electrodes (*n*) and the number of voltage magnitudes (*k*).

2) Sheet Thickness

As the reviewer concerned, the influence of sheet thickness and convection heat transfer conditions must be more thoroughly considered when scaling up to a larger, especially thicker, system form factor. In our work, the thickness was minimally configured to achieve a considerably swift shape-morphing process, while carefully selected to ensure the sufficient self-weight sustainability. We admit that the increase of the thickness is one of the drawbacks in our system, which would be due to the reliance to passive cooling via natural air convection. To address this concern, future efforts could incorporate additional cooling strategies, such as flexible thermoelectric elements [*Nat Commun* **15**, 2141 (2024)] or passive radiative cooling [*Nat Commun* **15**, 8000 (2024)], to enable an increase in film thickness while maintaining its swift responsiveness. This discussion has been included in manuscript as follows:

In Manuscript, Discussion (Highlight in concerning part):

Before:

... grasping and locomotion. Future improvements in these capabilities include geometrically scalable material designs (including metamaterials), intrinsic shape sensing, digital twinning toward data-efficient computation, and wireless drives, expanding the scope of versatile engineering methodologies by blending intelligence in morphology and computation.

After:

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Despite these promising features, several concerns should be addressed to further mature our technology. First, the mechanical performance should be improved to enhance both shape responsiveness and load-bearing capacity. Additional material advancements should be investigated beyond our micro-rod structure, including thermo-responsive meta-materials that outperform conventional materials[55], or a structural design with a thicker form factor that would require accelerated cooling mechanisms[56, 57]. Such modifications would enable more complex folding process featuring overlapping or curved folds. Second, the practical applications of the robotic sheet should be explored in greater depth, including potential demonstrations as a light modulator[47] or a dexterous robotic platform for environmental monitoring[58]. To this end, the replacement of wire-based interconnections to in-hardware electrode traces and the straightforward insertion of add-on elements, such as intrinsic shape sensing modalities, should be further investigated. Furthermore, the demonstration of generalized shape programmability with various form factors would extend the effectiveness of our framework that would incorporate the flexible assembly of unit elements across scales and dimensions. All these breakthroughs would expand the scope of versatile engineering methodologies by blending intelligence in morphology and computation.

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58. Kumar, V. *et al.* Microengineered Materials with Self-Healing Features for Soft Robotics. *Adv Intell Syst* **3**, 2100005 (2021)

Reviewer #2

[General review]

This paper presents a field-programmable "robotic sheet" featuring a very elaborate network of resistors and electrodes embedded in responsive material layers. Such a high-resolution resistor network can function as a thermal actuator and sensor, enabling on-demand, programmable folding with closed-loop feedback. The authors demonstrated the use of such robotic folding sheets via simple manipulation and locomotion tasks.

Overall, I found this work fascinating. The high resolution of thermal actuators/sensors is unprecedented in sheet-like morphing materials. More importantly, the seamlessly integrated closed-loop feedback control on folding presents a breakthrough in origami engineering. Therefore, this paper is an excellent fit for publication in Nature Communication.

The authors can further improve the paper by addressing some fundamental questions I have in mind.

[Our response]

We appreciate your insightful comments, which have greatly contributed to improving the quality of our paper. We have prepared responses to your comments as follows.

[Comment #1] Complexity of fold lines (folding pattern):

Origami folding is a great motivation for this study, and the authors demonstrated that their robotic sheets could show mountain and valley folds at different locations and different orientations. However, all these fold lines are simple, straight lines, and they do not intersect with each other. If we look at classical origami design (e.g., Miura-Ori, Water bomb base), a key feature is that their mount-valley fold lines will join at a point (aka., degree 4 or 6 vertexes), thus creating elaborate shapes. For the robotic sheet in this study, would it be possible to develop these kinds of complex folding shapes by patterning mountain valley folds and allowing vertices to form? More broadly, what kind of folding is possible beyond isolated bending?

[Our response]

In this study, experiments were conducted within a fixed temperature range to ensure repeatable operation. However, we have observed that overheating can also produce more complex patterns, such as a waterbomb pattern, as shown in **Figure R4**. Although this finding may be noteworthy compared to other electrothermal-actuator-based shape transformations, this overheating compromises the sheet's reliability, and the resulting buckling at the center leads to inconsistent shape changes. Therefore, further improvements are required to enhance the shape morphing performance. For instance, structural optimization would present an improved curvature range, making various complex folding patterns feasible. This discussion has been added to the manuscript as follows.

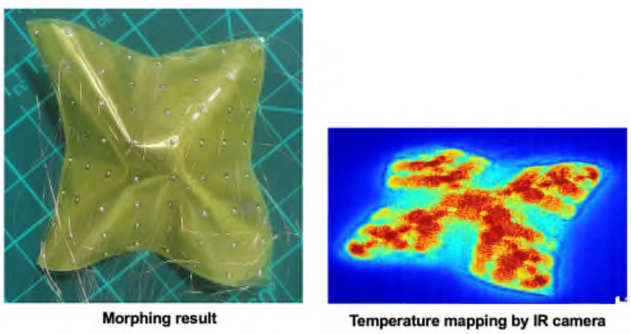


Figure R4. Demonstration of the waterbomb pattern (For response letter only)

In Manuscript, Discussion (Highlight in concerning part):

Before:

... grasping and locomotion. Future improvements in these capabilities include geometrically scalable material designs (including metamaterials), intrinsic shape sensing, digital twinning toward data-efficient computation, and wireless drives, expanding the scope of versatile engineering methodologies by blending intelligence in morphology and computation.

After:

... grasping and locomotion.

Despite these promising features, several concerns should be addressed to further mature our technology. First, the mechanical performance should be improved to enhance both shape responsiveness and load-bearing capacity. Additional material advancements should be investigated beyond our micro-rod structure, including thermo-responsive meta-materials that outperform conventional materials[55], or a structural design with a thicker form factor that would require accelerated cooling mechanisms[56, 57]. Such modifications would enable more complex folding process featuring overlapping or curved folds. Second, the practical applications of the robotic sheet should be explored in greater depth, including potential demonstrations as a light modulator[47] or a dexterous robotic platform for environmental monitoring[58]. To this end, the replacement of wire-based interconnections to in-hardware electrode traces and the straightforward insertion of add-on elements, such as intrinsic shape sensing modalities, should be further investigated. Furthermore, the demonstration of generalized shape programmability with various form factors would extend the effectiveness of our framework that would incorporate the flexible assembly of unit elements across scales and dimensions. All these breakthroughs would expand the scope of versatile engineering methodologies by blending intelligence in morphology and computation.

In Manuscript, Reference:

Newly Included:

55. Ni, X., Guo, X., Li, J., Huang, Y., Zhang, Y., Rogers, J. A. 2D Mechanical Metamaterials with Widely Tunable Unusual Modes of Thermal Expansion. *Advanced Materials* **31**, 1905405 (2019).

56. Liu, Y., *et al.* Fully inkjet-printed Ag_2Se flexible thermoelectric devices for sustainable power generation. *Nat Commun* **15**, 2141 (2024).

57. Kim, S., Lee, S., Lee, J. *et al.* Passive isothermal film with self-switchable radiative cooling-driven water sorption layer for arid climate applications. *Nat Commun* **15**, 8000 (2024).
58. Kumar, V. *et al.* Microengineered Materials with Self-Healing Features for Soft Robotics. *Adv Intell Syst* **3**, 2100005 (2021)

[Comment #2] Feedback control:

The feedback control on robotic folding is a commendable accomplishment. Would the authors give a more *quantitative* assessment of the control performance (from the angle of a robotics control engineer)? For example, what is the steady-state error between the targeted and actual folding angles? (PI controller, in principle, should give zero steady-state error, but that depends on the accuracy of the sensing). How much disturbance can the controller reject? Can a high proportional control gain help reduce the setting time, thus making the folding faster? (slow folding is always the Achilles heel of thermal-induced origami folding).

[Our response]

Upon the reviewer's constructive suggestion, a more quantitative assessment of the control performance was conducted through a transient response analysis. Since our control variable is temperature, we characterized the performance in detail with respect to the temperature. The transient response was examined under varying control parameters, P gain and I gain. Following generic consensus in control theory, it was observed that increasing the P gain accelerates the tracking performance, but excessive increase leads to a chattering effect. Meanwhile, increasing the I gain reduces the steady-state error, but excessive increase leads to overshoot, because our modulation strategy embeds a tight saturation of the control input. Based on the results, we justified our selection on the values (K_p =0.4, and K_i = 0.009). Moreover, we included the quantification of the control performance. The 5% settling time was shortened from 44.37 s (in open-loop control) to approximately 6.64 s, and the steady-state error was reduced from -1.13 °C (in P control) to 0.22 °C. We included these details to the manuscript as follows:

In Manuscript, Programming and Control, 5th paragraph:

Before:

... exhibiting reduced phase shift of approximately -85^{o} to -55^{o} at the bandwidth (Fig. 4d).

After:

... exhibiting reduced phase shift of approximately -85^{o} to -55^{o} at the bandwidth (Fig. 4d). A transient response analysis supports these improvements in control performance, especially in terms of settling time and steady-state error (Supplementary Fig. 19).

In Manuscript, Methods, Closed-Loop Temperature Control:

Before:

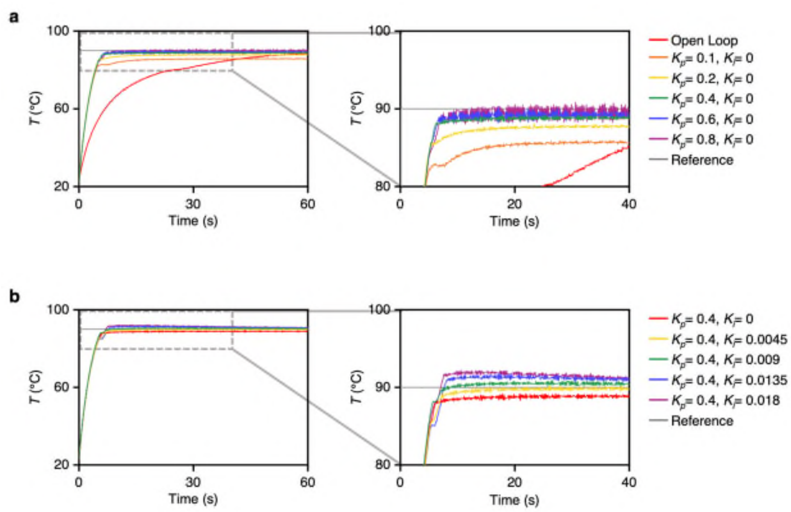
... set as 0.4, and 0.009, respectively.

After:

... set as 0.4, and 0.009, respectively. The selection process for these gains is detailed via a transient response analysis (Supplementary Fig. 19).

In Supplementary Information:

Newly Included:



Supplementary Fig. 19. Transient response analysis of the thermodynamics. a, Transient response of open-loop control and P control in electrothermal stimulation. The P gain (K_p) accelerates temperature tracking, but an excessive increase leads to a chattering effect. Based on this observation, the value of K_p was selected as 0.4. The selected P control yields a shorter settling time (5 %) compared to the open-loop control, displaying 6.64 and 44.37 s, respectively. **b**, Transient response with PI control. Given a fixed K_p (=0.4), the I gain (K_i) reduces the steady-state error, but an excessive increase leads to overshoot due to tight saturation of the control input. Based on this observation, the value of K_i was selected as 0.009. The selected PI control exhibits a lower steady state error than the P control, displaying 0.22 and -1.13 °C, respectively.

With all due respect, the quantitative evaluation on the degree of disturbance rejection was hard to investigate. This is because the thermal disturbance is highly stochastic in real world, and thus not repeatable and replicable. Specifically, we employed two types of disturbances in this work; wind and ambient temperature elevation. However, even in the latter case, which is slower and relatively more controllable in a sufficiently insulated chamber, the pattern of temperature elevation varied in both space and time.

[Comment #3] Load bearing capacity and Functionality?

Based on the robotic demonstration, the loading-bearing capacity seems relatively low. The targeted objects are all pretty lightweight. Therefore, I am unsure whether object lifting is the best use of this new robotic sheet. Could the authors explore other possible uses to better exemplify the advantage of such on-demand and closed-loop controlled folding/morphing?

[Our response]

As the reviewer mentioned, the load-bearing capacity is indeed relatively low. The limitation is attributed to the film-based form factor, although the mechanical response has been significantly improved through our precise material structuring. Nevertheless, our demonstrations of the most fundamental motions in the field of soft robotics, gripping and locomotion, would pave the way for achieving multifunctional capabilities within a single robotic hardware system through shape programming. Beyond these foundational capabilities, addition concepts can be explored using our platform. For example, a light modulator—such as the one presented in the paper by X. Ni [*Nature* **609**, 701-708 (2022)]—could potentially be implemented with our approach (**Figure R5** for initial result for feasibility). Furthermore, various external sensing modalities could be integrated onto our sheet to realize a more dexterous robotic platform for environmental monitoring, similar to the work of V. Kumar [*Adv Intell Syst* **3**, 2100005 (2021)]. However, many of these applications, beyond our current demonstrations, would require add-on components. For instance, a light-reflective sheet would require an ultra-thin mirror coating. While such approaches are feasible, they may affect the thermal and mechanical characteristics of the system. Therefore, with all due respect, we believe that many of these applications could be demonstrated as future extensions, building upon the foundational work presented here. We have included this discussion in the revised manuscript as follows:

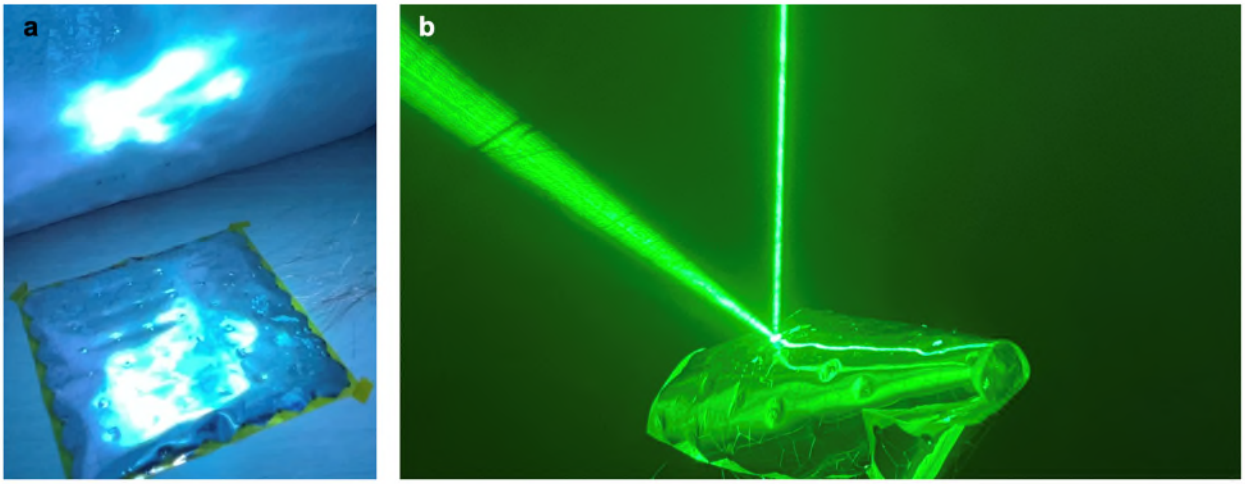


Figure R5. Example of light modulation using our approach (For response letter only). **a,** Our programmable sheet with a reflective coating. **b,** Laser modulation result by the fabricated sheet.

In Manuscript, Discussion (Highlight in concerning part):

Before:

... grasping and locomotion. Future improvements in these capabilities include geometrically scalable material designs (including metamaterials), intrinsic shape sensing, digital twinning toward data-efficient computation, and wireless drives, expanding the scope of versatile engineering methodologies by blending intelligence in morphology and computation.

After:

... grasping and locomotion.

Despite these promising features, several concerns should be addressed to further mature our technology. First, the mechanical performance should be improved to enhance both shape responsiveness and load-bearing capacity. Additional material advancements should be investigated beyond our micro-rod structure, including thermo-responsive meta-materials that outperform conventional materials[55], or a structural design with a thicker form factor that would require accelerated cooling mechanisms[56, 57]. Such modifications would enable more complex folding process featuring overlapping or curved folds. Second, the practical applications of the robotic sheet should be explored in greater depth, including potential demonstrations as a light modulator[47] or a dexterous robotic platform for environmental monitoring[58]. To this end, the replacement of wire-based interconnections to in-hardware electrode traces and the straightforward insertion of add-on elements, such as intrinsic shape sensing modalities, should be further investigated. Furthermore, the demonstration of generalized shape programmability with various form factors would extend the effectiveness of our framework that would incorporate the flexible assembly of unit elements across scales and dimensions. All these breakthroughs would expand the scope of versatile engineering methodologies by blending intelligence in morphology and computation.

In Manuscript, Reference:

Newly Included:

55. Ni, X., Guo, X., Li, J., Huang, Y., Zhang, Y., Rogers, J. A. 2D Mechanical Metamaterials with Widely Tunable Unusual Modes of Thermal Expansion. *Advanced Materials* **31**, 1905405 (2019).
56. Liu, Y., *et al.* Fully inkjet-printed Ag_2Se flexible thermoelectric devices for sustainable power generation. *Nat Commun* **15**, 2141 (2024).
57. Kim, S., Lee, S., Lee, J. *et al.* Passive isothermal film with self-switchable radiative cooling-driven water sorption layer for arid climate applications. *Nat Commun* **15**, 8000 (2024).
58. Kumar, V. *et al.* Microengineered Materials with Self-Healing Features for Soft Robotics. *Adv Intell Syst* **3**, 2100005 (2021)

<u>Reviewer #3</u>

[General review]

Shape-morphing structures, especially those inspired by origami and folding, are an emerging frontier in mathematics, computer science, and robotics. They enable devices to adapt their shape for different tasks or environments, providing embodied intelligence and versatility. Field-Programmable Robotic Folding Sheet addresses this frontier by presenting a thin robotic sheet that can be programmed after deployment to fold into various configurations on demand. This capability, termed “field-programmability,” is a significant advancement over traditional foldable robots with fixed hinges or predetermined fold patterns. The manuscript under review is highly relevant to the field, as it combines innovations in materials, actuation, and control to achieve reconfigurable 3D shapes from a 2D sheet. In the following, I outline the key strengths of this work, suggest minor improvements, and conclude with a strong recommendation for acceptance.

<Strengths>

1. Demonstrated Programmability of the Folding Sheet

The paper convincingly demonstrates that the robotic sheet’s folding pattern is fully programmable in situ. The same sheet can assume an unbounded set of hinge configurations post-deployment, meaning the location, direction, and angle of folds can be chosen and reprogrammed on the fly. This level of programmability is unprecedented—previous folding robots typically had fixed crease lines or could only cycle through a limited set of pre-designed shapes. Here, by contrast, the authors show the sheet forming diverse shapes (from basic bends and waves to more complex multi-fold geometries) all through electronic commands. This proves the concept of a single physical device being able to realize many structural forms, essentially treating shape as a software-controlled variable. The ability to reconfigure the folding profile repeatedly and reversibly in the field is a remarkable contribution to adaptive robotics.

2. Novel Use of Electrothermal Actuation for Shape Morphing

A core innovation is the sheet’s embedded electrothermal actuation system. The authors integrate a dense network of metallic resistive elements within a thermo-responsive polymer layer, creating “pixels” that can be individually heated. This is a novel application of electrothermal actuators in a distributed, sheet-like format. By Joule heating selected regions, the polymer folds along those lines; when heating is removed, it cools and can flatten back, enabling bidirectional (reversible) folding.

Importantly, each resistor not only acts as a heater but also as a sensor (thermistor), allowing the sheet to sense its own temperature distribution. This dual functionality enables a built-in feedback mechanism—often referred to as resistive network sensing—that the authors use for closed-loop control of the folding process. The electrothermal approach is shown to be fast, producing folds quickly, and strong enough to achieve large bending angles (on the order of ±90°). Unlike pneumatic or magnetic actuators used in other shape-morphing systems, this electronic heating method is self-contained (requiring no external fields or bulky equipment) and easily integrated with onboard electronics. The result is a robust and elegantly simple means of morphing the sheet’s shape with fine spatial addressability.

4. Expanding Programmable Matter through a New Methodology

This work introduces a new methodology for programmable matter, where a material system's physical configuration is programmable by the user. By blending materials (responsive polymer), hardware (embedded resistor network), and software (control algorithms for addressing and feedback), the authors create a sheet that behaves like a reconfigurable matter module.

The field-programmable folding strategy means the sheet's geometry is no longer fixed at manufacture—it can evolve and adapt on demand. This is analogous to how field-programmable gate arrays (FPGAs) allow circuits to be reprogrammed dynamically; here, the authors introduce a field-programmable mechanical structure. Such reconfigurability vastly expands the design space for shape-changing devices.

5. Potential Applications in Robotics, Autonomous Systems, and Materials Science

The manuscript does an excellent job of not only developing the technology but also illustrating its real-world applications. The authors present two compelling demonstrations:

Reconfigurable Robotic Gripper: The sheet is programmed to switch between multiple grasping modes (wrapping, pinching, multi-fingered hold) all within a single device. This adaptability allows for handling diverse object shapes with a gentle, conformal grip.

Shape-Shifting Locomotion Platform: The sheet crawls, walks, and waves across surfaces, mimicking bio-inspired movements such as inchworm crawling and rolling locomotion. Its recorded locomotion speeds (5–25 mm per cycle) showcase its potential as an untethered mobile robot.

Beyond these examples, autonomous shape-adaptive exploratory robots and deployable structures could leverage this technology, opening pathways for applications in space exploration, biomedical engineering, and soft robotics.

[Our response]

We sincerely appreciate your positive review and strong recommendation, along with your thoughtful and thorough analysis of the strengths of our research. Your encouraging feedback reinforces our confidence in the value and direction of our work. We have prepared responses to your comments as follows.

Minor Suggestions for Improvement

While this manuscript is already exceptionally strong, a few minor refinements could further enhance its impact:

[Comment #1] Clarification of Universality:

While the authors demonstrate the programmability of the sheet, a short explanation of how the box-pleated structure mathematically enables universal 3D shape formation (possibly with a simple diagram) would help clarify this crucial contribution.

A possible suggestion is to explain the integration of Box-Pleated Patterns for Universal 3D Shape Construction. For example:

An important mathematical foundation of this work is the incorporation of a box-pleated pattern into the robotic sheet's folding design. The box-pleated origami pattern has been mathematically proven to be universal, meaning that by appropriately arranging its folds, it can approximate any 3D shape that can be represented as a voxel-based model. This universality allows the robotic sheet to mimic arbitrary 3D geometries, providing a level of adaptability that extends beyond conventional origami-based shape morphing.

The robotic sheet uses a box-pleated origami pattern—a regular grid of creases with alternating diagonals—that enables it to fold into many tiny box-like segments. In simple terms, this means the sheet can partition itself into small cube-shaped units (voxels) by choosing certain creases to fold while leaving others flat. Mathematically, it has been proven that this type of crease pattern (tetrakis tiling) is universal, meaning that by adjusting its folds, it can represent any shape composed of unit cubes joined face-to-face. By using a fine enough grid, the sheet can approximate virtually any 3D form with arbitrary accuracy. Unlike custom fold patterns that must be designed for each shape, the box-pleat pattern provides a general-purpose mold that can realize a broad library of shapes simply by reprogramming fold activations.

This property has profound practical implications for robotics, adaptive structures, and programmable materials. A single field-programmable sheet can be instructed to morph into a multitude of structures or tools on demand. For instance, the same sheet might fold into a manipulatory gripper, then flatten and refold into a rolling wheel or deployable shelter, all without requiring reassembly. This shape-shifting material effectively acts like a reconfigurable "display" for 3D objects, where different geometries emerge based on selected fold sequences. The ability to generate any shape defined by a voxel-based model suggests a direct link between computational geometry and physical morphing, further strengthening the paper's contributions to the fields of robotics, materials science, and applied mathematics.

[Our response]

We deeply appreciate the reviewer's sincere suggestion on the theoretical support for our methodology. Indeed, we have envisioned our unit block approach as a foundation for a universal shape approximator, through its boundless arrangement across the scales and dimensions. We strongly believe a clearer presentation of this aspect can strengthen our contribution. Therefore, we have included the relevant discussions in the manuscript with additional references as follows (note that a concise description was included due to the word limit):

In Manuscript, Design and Principle, 1st paragraph:

Before:

...at the center of the unit lattice. The robotic...

After:

...at the center of the unit lattice. The unit structure closely resembles the box-pleated origami pattern, which can serve as a universal shape approximator with its flexible arrangement[39, 49]. The robotic...

In Manuscript, Discussion (Highlight in concerning part):

Before:

... grasping and locomotion. Future improvements in these capabilities include geometrically scalable material designs (including metamaterials), intrinsic shape sensing, digital twinning toward data-efficient computation, and wireless drives, expanding the scope of versatile engineering methodologies by blending intelligence in morphology and computation.

After:

... grasping and locomotion.

Despite these promising features, several concerns should be addressed to further mature our technology. First, the mechanical performance should be improved to enhance both shape responsiveness and load-bearing capacity. Additional material advancements should be investigated beyond our micro-rod structure, including thermo-responsive meta-materials that outperform conventional materials[55], or a structural design with a thicker form factor that would require accelerated cooling mechanisms[56, 57]. Such modifications would enable more complex folding process featuring overlapping or curved folds. Second, the practical applications of the robotic sheet should be explored in greater depth, including potential demonstrations as a light modulator[47] or a dexterous robotic platform for environmental monitoring[58]. To this end, the replacement of wire-based interconnections to in-hardware electrode traces and the straightforward insertion of add-on elements, such as intrinsic shape sensing modalities, should be further investigated. Furthermore, the demonstration of generalized shape programmability with various form factors would extend the effectiveness of our framework that would incorporate the flexible assembly of unit elements across scales and dimensions. All these breakthroughs would expand the scope of versatile engineering methodologies by blending intelligence in morphology and computation.

In Manuscript, Reference:

Newly Included:

49. Benbernou, N., Demaine E. D., Demaine, M. L., Ovadya A. A Universal Crease Pattern for Folding Orthogonal Shapes. *arXiv*, arXiv:0909.5388 (2009).

...

55. Ni, X., Guo, X., Li, J., Huang, Y., Zhang, Y., Rogers, J. A. 2D Mechanical Metamaterials with Widely Tunable Unusual Modes of Thermal Expansion. *Advanced Materials* **31**, 1905405 (2019).
56. Liu, Y., *et al.* Fully inkjet-printed Ag_2Se flexible thermoelectric devices for sustainable power generation. *Nat Commun* **15**, 2141 (2024).
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58. Kumar, V. *et al.* Microengineered Materials with Self-Healing Features for Soft Robotics. *Adv Intell Syst* **3**, 2100005 (2021)

[Comment #2] Discussion on System Limitations:

It would be beneficial to explicitly discuss practical constraints, such as durability over repeated cycles and energy efficiency. This could provide insights into long-term deployment scenarios and scalability for larger structures.

[Our response]

As the reviewer mentioned, durability and energy efficiency can offer valuable insights into a variety of practical features. With all due respect, the repeatability of our film has been demonstrated through 1,000 repetitions of a folding cycle, as shown in Figure 2f. Meanwhile, the energy efficiency has been newly estimated during this revision process (overall, 12.59%). We note that an average value was presented because the efficiency value is intrinsically dynamic. In response to the other reviewer's suggestion, we have also included a characterization of the system dynamics through a transient response analysis, which would explicitly display the performance limits of our actuation. The revision of the manuscript upon the reviewer's suggestion is as follows:

In Manuscript, Programming and Control, 5th paragraph:

Before:

... The required power consumption for corresponding morphing is shown in Extended data Fig. 9b.

After:

... The required power consumption for corresponding morphing is shown in Supplementary Fig. 18b, displaying a lumped conversion efficiency of 12.59 %.

These suggestions do not detract from the paper's excellence but are intended to make its contributions even clearer to a broad readership.

Conclusion and Recommendation

In summary, Field-Programmable Robotic Folding Sheet is an outstanding contribution that significantly advances reconfigurable robotics and smart materials. The authors introduce a new paradigm for dynamic shape programming, leveraging electrothermal actuation and computationally controlled folding. This work will be of great interest to researchers across robotics, materials science, and programmable matter.

I strongly recommend acceptance of this manuscript, as it meets the highest standards of scientific rigor, innovation, and relevance.

[Final remark]

We sincerely appreciate your valuable feedback once again, which has helped improve the quality of our manuscript and broaden the insights of our research. We have made our best efforts to incorporate your comments while clearly maintaining our core ideas.

Reviewer #4

[General review]

I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

[Our response]

We appreciate your dedication and support as a peer reviewer.