Miura-ori enabled stretchable circuit boards

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Origami, an ancient form of papercraft, provides a way to develop functional structures for engineering applications. In this paper, we report an approach to design and manufacture a stretchable circuit board (SCB) with origami structures. The benefits of developable, flat-foldable, and rigid-foldable origami-based structures as SCBs are discussed, and a representative structure, Miura-fold (or Miura-ori), is chosen to be investigated. Under the constraints induced by the mounted components’ dimensions, the Miura-ori structures for specific applications can be defined. We propose three methods for better fabrication, including direct folding, stiffness modification, and kirigami enhancement, to improve a planar sheet’s foldability. A wearable ECG (electrocardiogram) system based on MO-SCB (Miura-ori enabled SCB) technology is built, and the stretchable portion is made of commercial FPCBs (flexible printed circuit board), providing desired stretchability and reliability. The proposed technology routine is compatible with industrial production and may pave the application of stretchable electronics.

RESULTS AND DISCUSSION

Compatibility between origami structures and circuit boards

Developability, flat-foldability, and rigid foldability are crucial characteristics of an origami pattern29, revealing compatibility with the origami-based circuit boards. Nomenclatures and symbols related to the origami structures are defined in Supplementary Note 1.

- Developability is the condition of having an initial state with zero Gaussian curvature at every point26. The feature of developable origami is that it could be constructed by bending a planar surface according to the predesigned pattern without requiring extensional deformation26. It is necessary because the origami-based circuit board is made from a planar sheet, such as an FPCB.
- Flat-foldability is the condition of having a flat-, fully folded state26. Locally, by satisfying Maekawa’s theorem28 and Kawasaki’s theorem29, a flat-foldable degree-4-vertex (D4V), which are fundamental for Miura-ori patterns, can be flattened without being crumpled, bent, or damaged; globally, a flat-foldable origami pattern avoids self-collision of the sheet during the folding procedure by employing locally flat-foldable D4Vs everywhere30. Although globally flat-foldability is not a must due to the mounted components’ finite thickness, it is preferred for a more compact structure and higher deformability.
- Rigid foldability is the condition implying that no deformation in facets and crease lines is induced during folding/unfolding26. Ideally, rigid-foldable origami can realize a development mechanism even if the facets are all rigid panels31. It is a vital

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feature for the origami-based circuit board because it exerts minimal strain to the mounted components during deformation and extends the device’s lifespan.

**Geometry analysis of MO-SCBs**

As a representative structure of origami, Miura-ori is employed to design the MO-SCB. The ridge lengths \(a\) and \(b\), and the folding degree \(\phi (0 \leq \phi \leq 2\beta)\), defining the reduction of the zig angle or zag angle of the major creases during folding, can parameterize a cell of the Miura-ori structure, as shown in Fig. 1a. A full Miura-ori (Fig. 1b) consists of an array of such unit cells, and its overall dimensions: length \(L\), width \(W\), and height \(H\), can be expressed with the above four parameters and the number of facets \(N_l \times N_w\) (detailed in Supplementary Note 1).

The linear stretchability of a MO-SCB is defined as \(\epsilon = \frac{L_{\text{max}} - L_{\text{min}}}{L_{\text{min}}}\) and \(\epsilon^0 = \frac{W_{\text{max}} - W_{\text{min}}}{W_{\text{min}}}\), along with the major and minor crease directions (Fig. 1c), respectively, where symbols with subscripts max and min are the corresponding maximum and minimum dimensions. Some engineering considerations like residual deformation\(^{32,37}\), sheet thickness\(^{34-36}\), and external forces\(^{38}\) reduce the range of the folding degree \(\phi\) in a Miura-ori design (Fig. 2c).

- **Ideal folding range (RANGE I):** For an ideal Miura-ori structure with negligible sheet thickness and bending radius, the maximum and minimum in-plane dimensions are taken to be those in the flat-folded state\(^{38}\) and fully unfolded state, respectively.

![Fig. 1](https://example.com/fig1.png)

**Fig. 1  Geometry of the Miura-ori structure.** Schematics of a a unit cell of the Miura-ori, b a full Miura-ori structure, c a MO-SCB, and d the major creases of the pattern in zigzag. In b, \(N_l = 4\) and \(N_w = 4\); in c, \(N_l = 6\) and \(N_w = 8\). The minor(red) and major(blue) creases are defined based on parities, detailed in Supplementary Note 1. The top view of part of the structure (green area) in e shows that the projection of the minor crease (red) is collinear. For the major creases, the zig angle equals the zag angle, and the zag length equals the ridge length \(b\).

![Fig. 2](https://example.com/fig2.png)

**Fig. 2  Deformation of the Miura-ori patterned sheet.** a Schematics of the MO-SCB in different folding states (where \(N_l = 3\) and \(N_w = 4\)). (I) fully unfolded state, \(\phi = 0\) (i.e., before any process); (II) stable folding state, \(\phi = \phi_m\) (i.e., the state when packaging); (III) residual deformation state, \(\phi = \phi_0\) (i.e., relaxed state with residual deformation); (IV) most compact state, \(\phi = \phi_c\). b Schematic of a packaged MO-SCB. c Folding degrees \(\phi\) in different folding states. RANGE I: folding ranges from a fully unfolded state to a flat-folded state, requiring negligible thickness and bending radius. RANGE II: folding ranges from a residual deformation state to the most compact state; both the finite thickness and the elastic deformation of the MO-SCB lead to the reduction of the range of the folding degree \(\phi\) comparing with RANGE I. RANGE III: folding ranges from residual deformation state to stable folding state; incompressible packaging material (such as elastomer) protects the MO-SCB while reducing the deformation range comparing with RANGE II.

- Unpackaged bare MO-SCB folding range (RANGE II): However, inelastic materials, such as plastics and metals, have small residual deformation and cannot return to the original flat state (Fig. 2a-I) after folding, even when fully relaxed. An additional parameter defining the relaxed state of a practical MO-SCB—the residual folding degree \(\phi_0\) is introduced to characterize the residual deformation and is used to evaluate \(L_{\text{max}}\) and \(W_{\text{max}}\) (Fig. 2a-III). Moreover, due to the finite sheet thickness and elastic deformation, the ultimate folding state is \(\phi = \phi_c\) (most compact state, Fig. 2a-IV) instead of the ideal flat-folded state \(\phi = 2\beta\). Consequently, the folding status of a bare MO-SCB ranges from a residual deformation state to the most compact state.

- Elastomer encapsulated MO-SCB folding range (RANGE III): Furthermore, an incompressible elastomer encapsulates the Miura-ori structure (Fig. 2b), thereby protecting the MO-SCB and the electronic components but limiting the practical minimum in-plane dimensions \(L_{\text{min}}\) and \(W_{\text{min}}\). The Miura-ori structure is molded to the stable folding state \(\phi = \phi_m\) (Fig. 2a-II), with a specific dimension, an acceptable stretchability, and sufficient space to install electronic components. Thus, the folding range of a packaged MO-SCB shrinks—from a residual deformation state to a stable folding state, compared with a bare MO-SCB.

Unlike other Miura-ori enabled stretchable structures\(^{37,19,21}\), MO-SCBs carry electronic components on the facets’ surface, leading to a geometric constraint due to the components’ finite thickness and...
dimensions. The optimized design has been conducted to avoid the collision (or self-intersection in geometry) either between a component and MO-SCB surface (Supplementary Fig. 2b) or between components on neighboring facets (Supplementary Fig. 2c), which is discussed in Supplementary Note 2.

**Enhancing the foldability of the MO-SCB**

After several undesired designs (detailed in Supplementary Note 3), we realized the importance of developing a process to enhance substrate foldability. Unlike folding an origami structure whose creases have zero bending stiffness, it is almost impossible to fold a uniform plate without pretreated creases according to a designed pattern. Thus, three methods, including direct folding, stiffness modification, and kirigami enhancement, are proposed to improve a planar sheet's foldability to produce MO-SCB.

The most straightforward method is to apply concentrated forces at the creases, e.g., by pressing with a set of rigid molds, as crease pretreating. The advantages of this method include low fabrication complexity and no additional processing. Wrinkles which occur in the crease areas (Fig. 3), together with plastic deformation, facilitate the subsequent folding. However, it is quite hard to control the range of the wrinkles precisely, especially when the sheet is thick and/or the folding degree \( \varphi \) is large. Therefore, the method alone is not sufficient and employed to provide the initial direction, i.e., the folds' parity.

Stiffness modification, either stiffening the parallelogram facets or weakening the crease areas' bending stiffness, can improve the foldability. Noticing that the bending stiffness \( K \) scales with Young's modulus \( E \), the width of the plate \( b \) (not the parameter defining Miura-ori structure), and the cubed of the thickness \( t \), i.e., \( K \propto Ebt^3 \), we can modify the rigidity of the crease areas by reducing the thickness (reducing \( t \)), changing the material to a flexible one (reducing \( E \)), and removing parts of the region (reducing \( b \)).

Numerical simulation with SIMULIA Abaqus (detailed in Supplementary Note 4) based on the finite element method (FEM) is carried out to study bending stiffness modification on the folding process. Initially, the sheet is in a state of small residual deformation (\( \varphi_{\text{res}} = 6^\circ \), after the stage-1 folding). Figure 4a shows snapshots of the representative states of deformation of the structures of two thickness ratios, \( \phi_{\text{crease/facet}} = 0.05 \) and \( 0.39 \), under different levels of lateral compression, while the complete deformation processes can be viewed in Supplementary Movie 1, in which the color scale indicates the strain-energy density. The sheet with a given thickness ratio (e.g., 0.39, Supplementary Movie 1b) experiences two modes of deformation while compressed, the origami-dominated mode (or bent Miura-ori\(^{39,40} \)) and the global-buckling-dominated one\(^{39,41} \). The transition between the two modes may break the Miura-ori structure's symmetry, leading to irreversible damage to the MO-SCB. To study such transition, we investigate the total strain energies (Fig. 4b) and structural deformations of both a constrained Miura fold (Supplementary Movie 2a) and one condition in a global-buckling mode (Supplementary Movie 2b), aside from the free-standing structure shown in Fig. 4a. It is hypothesized that the transition happens when the structure's energy in the buckling-dominated phase is lower than that in the origami-dominated one, and the structure is sufficiently perturbed to overcome any energy barrier\(^{21} \). After the critical point in Fig. 4b, the global-buckling structure's energy is lower than that of the constrained Miura fold, and a mode transition may occur under perturbation. We construct the morphological phase diagram in Fig. 4c for the equivalent thickness ratio ranging from 5 to 40%, and the elastic modulus \( E \) held constant. The lower region (low stiffness ratio or low relative compression) corresponds to the origami-dominated mode, while the upper right (higher crease stiffness and more extensive compression) is likely to be dominated by buckling. Although the transition does not necessarily occur due to the existence of a finite energy barrier, we decided to avoid it for safety. The range of the origami-dominated zone is inversely correlated to the bending stiffness ratio. Therefore, the more significant modification in bending stiffness, the more extensive the manageable range in a folding process.

With the planar sheet's bending stiffness, the equivalent thickness ratios near the major and minor creases are derived in Supplementary Note 5, corresponding to the gray dashed lines in Fig. 4c. The specially-designed crease areas provide enough region to ensure that the stable folding degree \( \varphi_{\text{m}} \) (21°, i.e., \( \Delta W = 4.36 \text{mm} \)) falls into the origami-dominated mode, which is consistent with the experiment.

Vertexes are the weakest part of the Miura-ori structure due to geometrically sharp angles and the mechanically concentrated strain shown in Fig. 5. With the concept kirigami, which enhances classic origami structures by including cuts (or removal of materials) in addition to folds, we remove some parts not containing electrical connections\(^{21} \) near the vertexes, to reduce the stress in the facets where electronic components mount and improve the overall reliability of the system. The distributions of the maximum principal strain (logarithmic, LE) in a traditional Miura-ori structure and in kirigami-enhanced structures with thin slits and holes around the vertexes reveal that the strain at the center of the facets is effectively reduced by over 50% by employing the method. The strain decrease in the facets reduces the possibility of the debonding between mounted components and substrate. Moreover, the four creases and the four sectors of a vertex do not converge perfectly because of the substrate's finite thickness\(^{49} \), which causes the panels' interference. The holes enable the MO-SCB to deform freely\(^{21} \) (Supplementary Fig. 8), provide more DOFs (degree-of-freedom), and facilitate the folding process (Supplementary Movie 3).

To our knowledge, although the above principles are used every so often (regarded as employing the direct folding
itself, both direct folding and stiffness modification, both direct folding and kirigami enhancement, and all the three methods, there is no systematical investigation on them. The three methods collaborate to enhance the foldability. After employing direct folding, the crease areas’ stiffness is reduced due to irreversible deformation such as the wrinkles; the out-of-plane folding (as the stage-1 folding) defines the mountain-valley assignment initially, which is necessary for in-plane pressing (as the stage-2 folding). The narrower hinges from the kirigami enhancement decrease the equivalent bending stiffness. Besides, the combination of kirigami enhancement and stiffness modification effectively reduces the maximum strain in the facet areas and facilitates the folding process, as discussed in Supplementary Note 6.

**Mechanical and electrical performances**

After folding, the origami-based portion of the board shrank in-plane. The stretchability of the MO-SCB along with minor and major crease directions were 33.3% and 8.7%, respectively.
respective (Fig. 6a–c). Due to more DOFs introduced by the kirigami enhancement and the finite thickness of panels, the actual size did not perfectly match the theoretical one (derived in Supplementary Note 7). The Miura-ori structure enabled the board to be compressed to a 10 × 10 mm² square (i.e., over 75% stretchability) without damaging the circuit (as the most compact state, in Fig. 6d).

The planar sheet was bent in the crease areas, where the amount of strain on particular layers of the structure requires evaluation. Because the flexible materials allow much more elongation than the copper without fracturing, and the strain inside the copper layer is theoretically acceptable, as derived in Supplementary Note 8, the board should be able to survive in the repeated bending of the crease areas, i.e., repeated deformation of the MO-SCB. An experiment of monitoring the wires in the MO-SCBs after finite cycles of deformation was conducted, which verified the wire fatigue or cracks were not generated even after 3000 times cycling (detailed in Supplementary Note 9).

Both an origami-structured part and three wavy-structured connections of the MO-SCB were packaged. The dimension of the packaged device was 45 × 22 × 5 mm³, acceptable for wearable electronics (Fig. 7a–b). The packaged device survived after being stretched by about 40% along the long side (Fig. 7c), twisted (Fig. 7d), and bent (Fig. 7e). Because the low-modulus package provided extra stretchability besides protection, the device’s total stretchability was higher than that of the bare MO-SCB (discussed in Supplementary Note 10). There was no visible degradation (either mechanical or electrical) on the device after 100 cycles of stretching and recovery with a speed of 3 mm per second and an elongation of 12 mm (Supplementary Movie 4a).

Figure 8a shows the frequency response curves of the MO-SCB before folding, after folding, and after packaging, which was consistent with the theoretical value calculated from the official design tool (AD8232/AD8233 Filter Design Tool). Changes in electrical characteristics caused by the board and package’s deformation were negligible, as shown in Fig. 8b, where an ECG signal generator (Mingsheng SKK-2000C, 60 bpm, 1 mV) was used as the input. The waveform corresponding to the human body test reveals the effectiveness of extracting the heartbeat. The raw data collected was processed by applying a low-pass Butterworth filter (40 Hz cutoff) in MATLAB, and the noise, mainly powerline sourced (50 Hz), did not affect the extraction of necessary information (such as heart rate) and could be filtered if necessary. Furthermore, the above stretchable part of the system was connected to the rigid part to form portable hardware, and it was paired with a smartphone via BLE (Bluetooth Low Energy, Fig. 8c). The smartphone provided a graphic interface to control the hardware. Figure 8d shows the app on which the waveform, average voltage, and sampling position of the ECG signal, the remaining battery, and button control for connection were placed.

MO-SCB: trends and futures

MO-SCBs can realize fast commercialization and pave the application of stretchable electronics. The initial substrate is a commercial FPCB, which is well developed in the industry. Almost all high-performance electronic components are rigid, requiring a low-strain facet’s handling (stretchable substrates’ shortcoming because of the structural incompatibility) and a high-density routine (two-dimensional interconnections’ disadvantage) and the proposed MO-SCB is promising to meet the requirements, as discussed in Supplementary Note 11.

Furthermore, the proposed MO-SCB technology can be used in other structures inspired by Miura-ori, serving as a Miura-ori family, as described in Supplementary Note 12. It is believed that
Margins for significant waveforms on the screen. The raw data collected was processed by applying a low-pass Butterworth generator was used as the input of the ECG monitoring module for the waveforms corresponding to initial, after folding, and after packaging. The theoretical frequency response is calculated from the Tool provided by Analog Devices (NASDAQ: ADI). ECG waveforms. Measured with Tektronix—TBS1052B. An ECG signal generator was used as the source. The ECG signal serves as the source. The ECG signal generator serves as the source. The signal was collected from one of the authors, Mr. Li Yongkai’s wrists.

**METHODS**

**System architecture and geometric design**

A wearable ECG monitoring circuit was designed and manufactured based on the proposed MO-SCB technology, as shown in Fig. 9. It has been revealed that the larger the component size, the larger each parallelogram facet in the Miura-ori pattern, leading to an increase in the Miura-ori structure’s height, i.e., the thickness of the MO-SCB. When the SCB is too thick, it may not be acceptable for wearable devices and applications. To balance the thickness of the MO-SCB and the functionality of the system, we only placed the ECG monitoring module on the MO-SCB; other large components, such as the ADC & Wireless Tx Module, and battery, required a rigid PCB for their placements. A smartphone could receive and process the collected data and demonstrate the ECG waveforms on the screen.

The Miura-ori pattern was determined according to the size of the most significant component (ADI, AD8233ACBZ) mounted on the MO-SCB. Margins for x and y directions were set to 50% of the devices’ dimensions to ensure robustness. For the MO-SCB in the ECG monitoring system, the constant $N_x$ and $N_y$ were set to 5 and 6, respectively. Moreover, the residual folding degree $\phi_0$ was set to $2^\circ$ to characterize the residual deformation. To facilitate the circuit board design with computer-aided design software, we chose $[a, b, \beta] = [4.5\, \text{mm}, 3.9\, \text{mm}, 66^\circ]$ as the variables for the pattern; when $\phi_m = 21^\circ$, the desired height, and stretchability along the minor crease direction are $3.13\,\text{mm}$ and $28.0\%$, respectively, as derived in Supplementary Note 7.

**Process for fabricating the MO-SCB**

We chose a commercial FPCB as the primary substrate of the MO-SCB. The FPCB consisted of a double-side RA FCCL (rolled-annealed flexible copper clad laminate, thicknesses of polyimide layer and each copper layer was 12 μm including adhesive), as shown in Fig. 4f. Rolled-annealed (RA) copper was chosen instead of electrodeposited (ED) due to the robustness against crack initiation and crack propagation.

According to our latest design, each facet’s circuits were rearranged to be interconnected by 4 or 6 parallel connecting lines over the creases (Fig. 10b). There was only one metal layer in the crease areas, making them treated as a single-layer FPCB (Fig. 10c). Furthermore, inspired by the concept kirigami, materials around the vertexes were entirely removed to facilitate the circuit board design with computer-aided design software, we chose $[a, b, \beta] = [4.5\, \text{mm}, 3.9\, \text{mm}, 66^\circ]$ as the variables for the pattern; when $\phi_m = 21^\circ$, the desired height, and stretchability along the minor crease direction are $3.13\,\text{mm}$ and $28.0\%$, respectively, as derived in Supplementary Note 7.

**Fig. 9** Block diagram of the ECG monitoring system.

**Fig. 8** Electrical test for the MO-SCB. a The frequency response of the MO-SCB (@$V_p, p_m = 1 \, \text{mV}$). The theoretical frequency response is calculated from the Tool provided by Analog Devices (NASDAQ: ADI). b ECG waveforms. Measured with Tektronix—TBS1052B. An ECG signal generator was used as the input of the ECG monitoring module for the waveforms corresponding to initial, after folding, and after packaging. The raw data collected was processed by applying a low-pass Butterworth filter (40 Hz cutoff) in MATLAB. c Schematic of the ECG monitoring system. The ECG signal generator serves as the source. d A screenshot of the Android app showing the outputs. The signal was collected from one of the authors, Mr. Li Yongkai’s wrists.
DATA AVAILABILITY
The data that support the findings of this study are available from the authors on reasonable request. The authors declare that the data supporting this study’s findings are available within the article and the corresponding supplementary information files.

CODE AVAILABILITY
This research does not have custom code or mathematical algorithm that is deemed central to the conclusions.

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Fig. 10  Schematic diagram of the process of making a MO-SCB from an FPCB. a–c Without a folding process, i.e., in the fully unfolded state. View from a top, b bottom, and c cross-section along A–A (not to scale). Wavy lines serve as connections between the board and electrodes. The longer one is used for power (VCC/GND) and output (OUT/LOD) function. The other pair of shorter wires are used for ECG signal collection. The parallelogram facets are interconnected by four (inset I: for major creases) or six parallel (inset II: for minor creases) connecting wires over the creases. LOD lead-off detection. d Processes and the real MO-SCB corresponding to the processes. (I) (optional) sealing with glob-top; (II) stage-1 folding; (III) stage-2 folding; (IV) elastomer packaging. e Molds help in shaping the origami-structured parts. The folding degrees of the 1st-level (transparent) and 2nd-level (white) molds are 10° and 24°. f Schematic of the cross-section of a packaged MO-SCB. (not to scale). Scale bars in b, e, and the insets of d represent 10 mm, while that in the insets of b is 1 mm.
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