

MetaCanvas: A Toolkit for Prototyping Tessellation-Based Shape-Changing Structures by Cut-and-Configure Authoring

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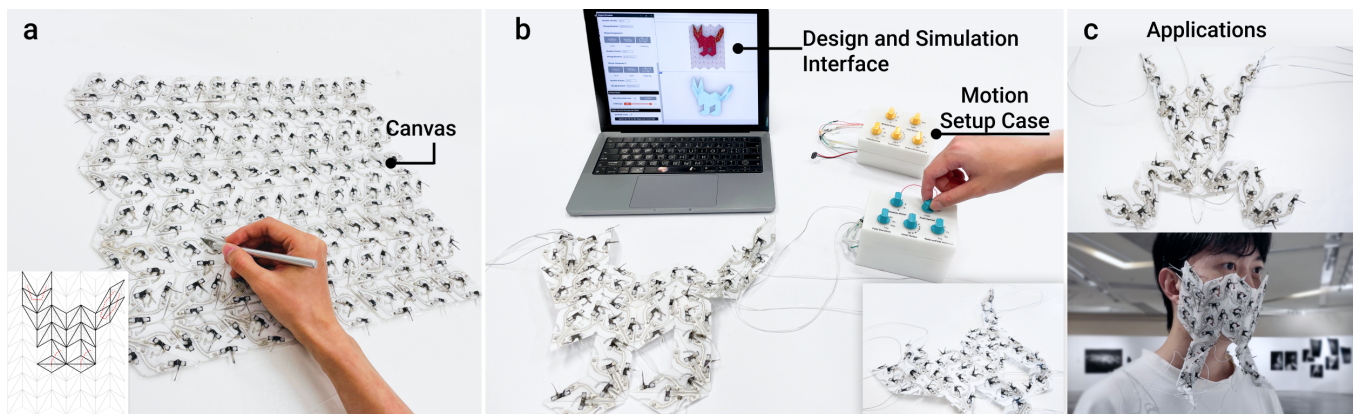


Figure 1: MetaCanvas supports a cut-and-configure workflow on a reusable actuated tessellation substrate. (a) Users cut the active canvas to define the artifact outline. (b) The Design and Simulation Interface specifies outlines, motion regions, and circuit assignments; the Motion Setup Case tunes temporal parameters on the fabricated artifact. (c) Applications. Top: A frog demonstration with independently actuated limbs; bottom: a wearable-expression concept with replaceable side modules.

Abstract

Origami tessellation offers a promising substrate for shape-changing interfaces, yet prototyping such structures remains labor-intensive: users often need to assemble modular parts or rebuild structures to explore alternative forms and motions. This limits rapid iteration, especially when motion behavior needs to be revised after fabrication. We present MetaCanvas, a prototyping toolkit that supports the design of tessellation-based shape-changing structures through a reusable active canvas and a cut-and-configure workflow. The toolkit combines a pre-fabricated tessellation substrate with embedded actuation, a digital interface for specifying cut patterns and

motion regions, and a tangible controller for adjusting actuation parameters without re-fabrication. This workflow enables users to customize shape and iteratively tune motion on the same canvas. We evaluate MetaCanvas through technical characterization, five demonstration artifacts, and a design study with 12 participants. The results show that MetaCanvas supports rapid customization of tessellation structures, localized motion design, and post-fabrication exploration of shape-changing behaviors. Based on these findings, we discuss how reusable and reconfigurable substrates can broaden the design space of shape-changing interface prototyping.

CCS Concepts

• Human-centered computing → Systems and tools for interaction design.

Keywords

Origami tessellation, Prototyping toolkits, Metamaterials, Computational design, Developable surfaces

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1 Introduction

Shape-changing interfaces bring computation into the physical world by expressing digital states through changes in form, motion, and material behavior [20, 41]. Among the structural strategies explored in HCI [23, 37, 47, 58], origami tessellations have emerged as a compelling substrate because repeated geometric patterns such as Yoshimura, Miura, and Kresling can produce predictable yet expressive deformations [6, 50]. Their foldable geometry, regular motion behavior, and visual appeal have motivated a growing body of work on interactive artifacts and prototyping toolkits based on tessellated structures [6, 45].

Despite this promise, prototyping tessellation-based shape-changing structures remains difficult. Many existing approaches require users to assemble pre-fabricated modules or fabricate a new structure for each design iteration [6, 58]. As a result, the final prototype is often constrained by a predefined module geometry, coarse motion regions, or fabrication workflows that are difficult to revise once the structure has been built. For users with limited origami or electronics expertise, this makes it hard to explore alternative forms quickly, recover from fabrication mistakes, or refine motion behavior after fabrication. Current workflows therefore make shape and motion customization possible, but they do not make iteration easy.

One way to address this challenge is to treat tessellation-based structures as mechanical metamaterials whose global behaviors emerge from the geometry and arrangement of local unit cells rather than from the base material alone [2, 18]. In HCI, this perspective opens up opportunities to treat tessellated structures as programmable physical substrates. By embedding actuation and conductive pathways into local cells, users can create localized deformation, reconfigurable motion, and integrated transformation behaviors without relying entirely on bulky external mechanisms or complex assembly [2, 5, 54]. Prior work has demonstrated many relevant actuation strategies for dynamic materials and shape-changing interfaces, including wires [36, 58], shape-memory alloys (SMAs) [16, 32], fluids [6, 21], motors [33, 38], pneumatics [13, 57], and magnetism [14]. These strategies, however, do not resolve the workflow problem on their own. Users still need accessible ways to customize and revise both form and motion on a physical prototype.

To support this kind of iteration, we present MetaCanvas, a prototyping toolkit for tessellation-based shape-changing structures that combines a reusable active substrate with a cut-and-configure workflow (Fig. 1). Rather than asking users to assemble a structure from modular parts or fabricate a new prototype from scratch, MetaCanvas lets them customize a pre-fabricated tessellation canvas with embedded SMAs and conductive traces through cutting, circuit assignment, and motion tuning. The toolkit integrates three components: a reusable active canvas composed of actuated triangular unit cells with SMAs; a Design and Simulation Interface for

specifying outlines and motion regions and previewing transformations; and a portable Motion Setup Case for adjusting motion order, speed, actuation duration, repetition count, and the interval between folding and unfolding directly on the fabricated artifact. A typical MetaCanvas workflow distributes authoring across digital and physical stages. Users first explore candidate shapes and motion regions in the Design and Simulation Interface, which previews approximate transformations and exports the cut outline together with the corresponding circuit schematic. Guided by this schematic, users then cut the physical canvas—rather than assembling separate modules or manually attaching SMAs—connect the relevant motion regions by sliding actuators into place, and refine temporal motion parameters on the artifact itself.

We evaluate MetaCanvas through technical characterization, five application examples, and a design study with 12 participants. Together, these investigations examine how MetaCanvas supports form customization, localized motion design, and iteration across its digital planning and physical configuration stages. Our findings show that MetaCanvas enables users to create diverse tessellation-based structures, repair or reinterpret locally mis-cut prototypes when fabrication errors occur, and keep revising motion without rebuilding the entire artifact. More broadly, the work points to the value of reusable active substrates for expanding shape-changing prototyping beyond one-off fabrication.

In summary, this paper makes three contributions:

- **MetaCanvas**, a reusable prototyping toolkit that combines an active tessellation canvas, a design and simulation interface, and a tangible controller that supports a cut-and-configure workflow for tessellation-based shape-changing structures.
- A **technical characterization** of active unit cells and structure-level behaviors, showing how localized deformation and motion tuning can be achieved across different tessellation configurations.
- **Application examples and a design study** demonstrating how reusable active substrates support rapid customization, post-fabrication iteration, and broader exploration in shape-changing interface design.

2 Related Work**2.1 Hands-on Toolkits for Prototyping Shape-Changing Systems**

Recent HCI research has lowered the barrier to shape-changing prototyping by offering hands-on toolkits that let users assemble, customize, or craft dynamic structures without engineering each device from scratch. MiuraKit [6] and PneuBots [57] support novice exploration of pneumatic shape change through modular construction, while MorphMatrix [7] and Mimosa [28] frame shape change as a toolkit problem for design exploration rather than a one-off engineering task [6, 7, 22, 28, 57]. 4Doodle [48] similarly broadens access to transformable artifact fabrication by replacing specialized 4D-printing workflows with a more craft-oriented process.

The systems closest to our work are ThreadTessel [58] and Robotic Metamaterials [5]. ThreadTessel provides a modular origami-tessellation toolkit for thread-actuated shape-changing structures, while Robotic Metamaterials enables hands-on configuration of repeated-cell dynamic applications through modular active units.

In these systems (Table 1), iteration still happens primarily through assembly: users recompose modules, connectors, or active cells to try alternatives. MetaCanvas instead contributes a pre-instrumented origami-tessellation substrate that users reconfigure through subtractive cutting and post-fabrication tuning. This shifts iteration from rebuilding structures out of parts to locally revising cut geometry and motion regions on the same pre-instrumented sheet.

2.2 Origami and Kirigami Interfaces for Shape Change

Origami and kirigami have long served as promising structural approaches for shape-changing interfaces because their geometry supports repeatable and expressive transformations. Prior work has explored foldable and cuttable structures for deformable displays and interactive surfaces, such as Origami Tessellation Display and KirigamiTable [12, 23], as well as expressive and aesthetic motion in systems such as ex-CHOCHIN and ElectriPop [9, 37]. Other projects have investigated computational design and fabrication pipelines for foldable artifacts, including Crane, Inkjet 4D Print, and additive origami fabrication approaches [1, 27, 35, 45, 47].

These systems demonstrate the expressive and fabrication potential of foldable structures, but they are typically presented as task-specific artifacts, fabrication pipelines, or single-interface exemplars. MetaCanvas differs in scope. Rather than presenting another stand-alone artifact, we focus on a reusable prototyping substrate that combines structural customization, localized actuation, and iterative tuning within the same origami sheet.

2.3 Reconfigurable Metamaterials and Motion Design for Active Structures

Mechanical metamaterials offer a second relevant lineage for our work because their behavior emerges from geometry and repeated cell structure rather than only material composition [2, 15, 46, 50]. HCI has increasingly adopted this perspective to create reconfigurable dynamic materials and shape-changing interfaces [5, 13, 17–19, 26, 30, 39, 44]. Two directions are especially relevant here. First, repeated-cell materials can be reconfigured through modular or sparse actuation, as in Reconfigurable Elastic Metamaterials, Robotic Metamaterials, Sparsely Actuated Modular Metamaterials, and Flextiles [5, 16, 38, 55]. Second, motion itself can be treated as a design variable, with prior work exploring trajectory, sequencing, and temporal tuning in systems such as AnimaStage, Magnetform, InflatableBots, and Waxpaper Actuator [11, 34, 53, 56].

MetaCanvas builds on these directions by bringing together cell-level structural programmability and post-fabrication motion tuning into a single end-user workflow. Rather than separating geometry, actuation layout, and timing into different design stages, our system lets users define motion regions on a pre-instrumented tessellation sheet, preview approximate transformations, and then refine order, speed, and duration after physical configuration.

3 System Design and Fabrication

MetaCanvas is a reusable actuated tessellation substrate designed for a hybrid digital–physical cut-and-configure workflow. It consists of three integrated components: (1) an active canvas composed of pre-fabricated tessellated unit cells, (2) a Design and Simulation

Interface for specifying cut outlines, motion regions, and circuit layouts, and (3) a portable Motion Setup Case for adjusting motion timing after fabrication. Rather than asking users to rebuild structures from modular parts or re-fabricate a new prototype for each revision, MetaCanvas supports continued iteration on the same pre-instrumented canvas through cutting, actuator reassignment, and post-fabrication motion tuning. Four goals guided the hardware design: keeping unit cells reusable, enabling easy activation and deactivation of individual hinges, isolating fold and unfold actuation on the same hinge, and preserving a sheet that remains cuttable.

3.1 Tessellation Unit Cell

The active canvas is built from two triangle geometries derived from Yoshimura- and Kresling-style tessellations. Each triangle has a 30° apex angle, a height of 2 cm, and a thickness of 1.5 mm (Fig. 2b). Pairing the two geometries yields two unit-cell configurations: Unit Cell A for the Yoshimura canvas and Unit Cell B for the Kresling canvas. To support post-fabrication reconfiguration of motion regions, each triangle pair is combined with a movable actuator carrier at the hinge. The carrier moves along a quarter-circular slider rail with a radius of 7 mm and acts as a movable electrical bridge. When the actuator is parked on one triangle, the hinge remains outside the active circuit. When the actuator is slid to the hinge midpoint, it electrically includes that hinge in the selected motion region (Fig. 2d). This mechanism allows users to redefine actuation regions on an already fabricated canvas without rebuilding the structure.

We fabricate the unit cells from selective laser sintering (SLS)-printed nylon because it remains thermally robust and structurally stable under repeated actuation. Each unit cell weighs approximately 3 g.

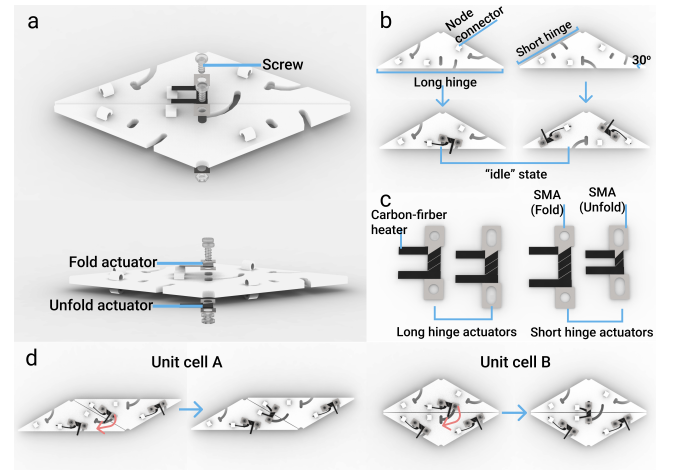


Figure 2: Actuated unit-cell construction. (a) Exploded and assembled views with fold and unfold actuators. (b) Two base triangle geometries and their idle state. (c) Four actuator variants for long/short hinges and fold/unfold actuation. (d) Unit Cell A (Yoshimura) and Unit Cell B (Kresling) transitioning from idle to active states.

Table 1: Comparison with hands-on shape-changing prototyping systems. MetaCanvas supports iteration by revising geometry and motion regions on the same actuated sheet rather than rebuilding from parts.

Work	Construction	Active element	Reconfiguration unit	Post-fabrication iteration
PneuBots [57] MiuraKit [6]	Modular assembly Modular assembly	Pneumatic modules Pneumatic origami tubes	Segment / connector Module / connector	Rebuild assemblies and reroute air paths. Reassemble modules into new structures.
ThreadTessel [58]	Modular tessellation assembly	Thread actuation across unit groups	Module / tessellation group	Recompose pieces and reroute threads.
Robotic Metamaterials [5]	Repeated-cell material with modular actuation	Detachable active cells	Cell / active-unit placement	Reassign active units within a repeated-cell structure.
Sparsely Actuated Modular Metamaterials [38]	Repeated-cell material with sparse actuation	Sparse modular add-ons	Cell / flexibility pattern	Adjust flexibility pattern and add actuation modules.
MetaCanvas	Cut-and-configure pre-instrumented sheet	Embedded local actuation + tuning case	Cut-defined cell pairs / motion regions	Locally revise cut geometry and motion regions on the same sheet, then retune temporal behavior without rebuilding.

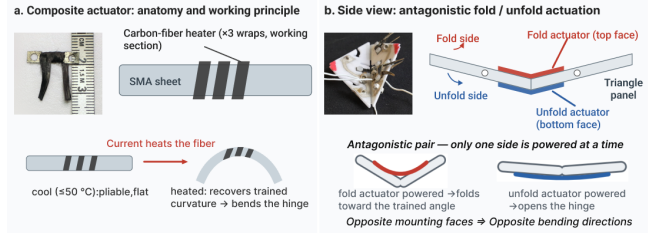
3.2 Composite SMA Actuator and Conductive Routing

To achieve a thin form factor, fast response, and silent operation compatible with a cuttable, sheet-like substrate, we chose SMA sheets over motors or pneumatic actuators. Each hinge is driven by a composite actuator consisting of an SMA sheet [29] wrapped with a carbon-fiber heater; current through the heater warms the SMA sheet, causing it to recover its trained curvature and bend the hinge. We adopted this design after pilot tests showed that direct electrical heating of the SMA sheet required substantially higher current (≥ 2 A) and damaged both the conductive traces and the nylon substrate. By contrast, the carbon-fiber heater generated sufficient heat at much lower current (≥ 0.2 A) and produced more stable actuation in our prototype. Conductive silver paint is applied to the triangle surfaces to create local pads and traces [10, 59]. When users slide selected actuators into place, these traces form a valid series circuit through the chosen motion region.

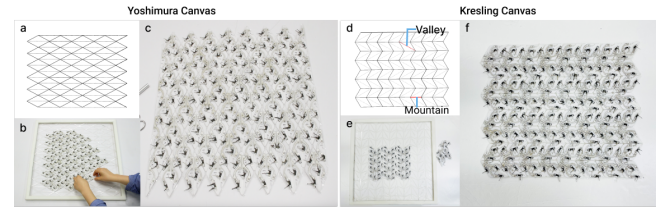
We use series routing because it keeps the circuit electrically simple: all actuators in a motion region share the same drive current and are driven by a single Motion Setup Case channel. In addition, localized actuation mechanically propagates deformation into adjacent passive regions, enabling visible transformation without activating every unit cell. We implemented four actuator variants, which differ in hinge length (long/short) and fold/unfold mounting side, to accommodate long and short hinges on both sides of the unit cell. Fold and unfold actuators are mounted on opposite faces of the same hinge and therefore bend it in opposite directions (Fig. 3). Each opposing fold–unfold actuator pair is secured with nylon screws to electrically and thermally isolate the two sides of the same hinge, minimizing cross-talk during alternating actuation (Fig. 2a and 2c). Throughout the paper, the “active” side refers to the side powered in a given trial.

3.3 Canvas Assembly

We fabricated two desk-scale 8×8 canvases: a Yoshimura canvas and a Kresling canvas. Within each unit cell, the two triangles are connected by 3-mm-wide thermoplastic polyurethane (TPU) tape, which defines the valley fold. For full-canvas assembly, we laser-cut a TPU tape net that defines the mountain folds and tension it on a


Figure 3: Composite SMA actuator and antagonistic fold–unfold actuation. (a) The carbon-fiber heater warms the SMA sheet, which recovers its trained curvature. (b) Actuators mounted on opposite hinge faces produce opposite rotations when powered separately.

supporting frame. Pre-fabricated unit cells are then inserted into the net to form the active canvas. This assembly step belongs to toolkit fabrication rather than the primary end-user iteration workflow (Fig. 4). Once the canvas has been prepared, users mainly iterate by cutting the desired outline, selecting active hinges, and tuning motion parameters. TPU-tape hinges allow cut-out cells or regions with intact traces and carriers to be reattached for local revision or reuse in new compositions.


Figure 4: Two reusable active canvases: (a–c) Yoshimura and (d–f) Kresling, each showing the unit-cell layout, insertion into the TPU net, and the assembled 8×8 canvas.

3.4 Motion Setup Case

To support post-fabrication motion tuning, we developed a portable Motion Setup Case (Fig. 5) that controls one motion region at a

time. The case exposes discrete settings for motion order, speed preset, actuation duration, repetition count, and the interval between folding and unfolding. Rotary switches send these settings to an ESP32-S3 microcontroller, which drives two MOSFET channels: one for folding and one for unfolding. To avoid simultaneous antagonistic actuation, only one channel is activated at a time. Power is supplied by a 5 V Li-ion battery, and the case connects to the selected motion region through external wires. Temporal settings can be changed without rewiring; only regrouping regions or assigning independent control requires reconnection or additional cases. Rather than exposing low-level actuation programming, the case translates characterization results into a small set of user-facing controls.

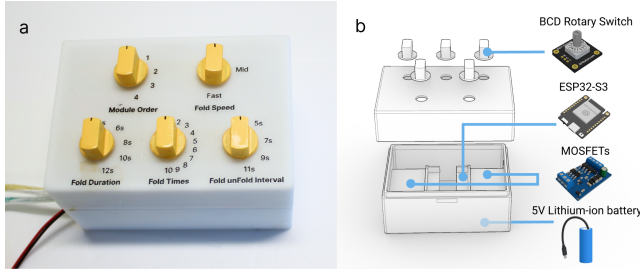


Figure 5: Motion Setup Case for post-fabrication tuning: (a) external controls and (b) internal electronics.

3.5 Design and Simulation Interface

The Design and Simulation Interface supports shape design, motion-region assignment, and fabrication export. From either a sketch on the tessellated canvas or an imported reference image, it generates a design outline over the tessellated grid. Users then assign candidate motion regions, preview approximate folding behavior before fabrication, and export the resulting cut outline and corresponding circuit assignment for physical construction. The interface thus lowers iteration cost: users explore shapes and motion regions and resolve circuit routing digitally via the auto-generated guide before committing to subtractive cuts on the physical canvas.

We implemented the interface in Rhino/Grasshopper with Kangaroo for interactive folding preview and a custom graph-search routine for circuit-path generation. The simulation is intended as an interactive design aid rather than a high-fidelity physical predictor. Accordingly, the previewed fold range is constrained to the empirically supported operating envelope measured in our technical characterization. The interface also includes a library of predefined parametric components for basic motion patterns such as spiral, collapsing, and circular forms (Fig. 10). These components can be attached to an existing shape and adjusted interactively; a collision-avoidance procedure prevents invalid overlaps during composition.

4 Technical Characterization

We characterize MetaCanvas at both the cell and structure levels to identify its operational envelope and design constraints. Specifically, we examine (1) how current affects folding performance, (2) thermal response and timing limits, and (3) the effects of structural coupling at both single-cell and multi-cell scales. Unless otherwise noted,

all measurements used the actuator configuration selected in the preliminary actuator-selection study reported in Appendix C and currents of 0.25, 0.30, 0.35, 0.40, and 0.45 A. We ran 15 trials for each condition. Folding duration was measured from electrical actuation onset to the first stable terminal configuration—the folded endpoint at which continued actuation at the tested current yielded no further angle change. We defined the terminal fold angle as the angle on the folding side between the two triangular panels adjacent to the actuated hinge. We measured this angle from side-view images captured with a fixed camera aligned with the hinge axis to reduce perspective distortion. Ambient temperature during thermal measurements was 24°C.

4.1 Cell-Level Performance Under Different Currents

We first measured folding duration and terminal fold angle for Unit Cells A and B across currents from 0.25 A to 0.45 A. As shown in Fig. 6, folding duration decreased nonlinearly as current increased for both long- and short-hinge actuators, and complete folding took less than 10 s at 0.40 A and above. Based on these results, we expose three discrete speed presets in the Motion Setup Case—Low, Medium, and High—rather than continuous current control. This balances responsiveness, thermal robustness, and ease of on-device parameter selection.

The measured terminal fold angles consistently exceeded the SMA training angle, which defines the target terminal angle. Because larger angles indicate shallower folding, the unit cells did not reach the target fold depth. We attribute this discrepancy to mechanical coupling between adjacent actuators and the gravitational load of the nylon triangles, both of which limit achievable folding. Accordingly, we constrain the interface preview to the empirically observed actuation envelope to avoid overestimating fold depth.

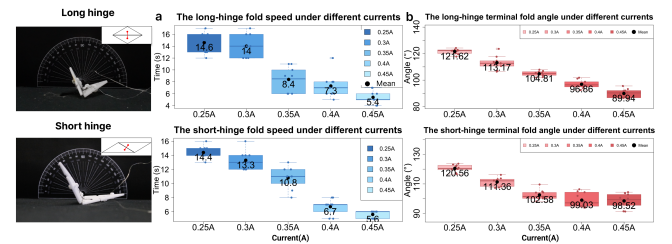


Figure 6: Fold duration and terminal fold angle under currents from 0.25 A to 0.45 A. (a) Complete actuation duration decreases from approximately 14.5 s to 5.5 s. (b) Terminal fold angle decreases from approximately 121° to 90°.

4.2 Thermal Response and Timing Constraints

We next measured heating and cooling behavior with a thermal camera (HIKMICRO B-series) for both long- and short-hinge actuators at 0.3 A and 0.4 A. In each trial, we applied power for 20 s and recorded both the active and inactive sides of the unit cell (Fig. 7). At both currents, the active actuator returned to a pliable state ($\leq 50^\circ\text{C}$) within about 10 s after power removal. Higher current reduced the onset delay of visible deformation during actuation but slightly increased the time required to cool to a pliable state.

These observations informed the Motion Setup Case presets. The actuation duration setting represents the driving period counted from the onset of visible deformation and excludes the initial heating period, because visible motion appeared only after a heating delay: the delay was 4 s under 0.4 A actuation and 6 s under 0.3 A actuation. Because the triangular substrate began to deform at 123°C, we capped the maximum folding time at 13 s.

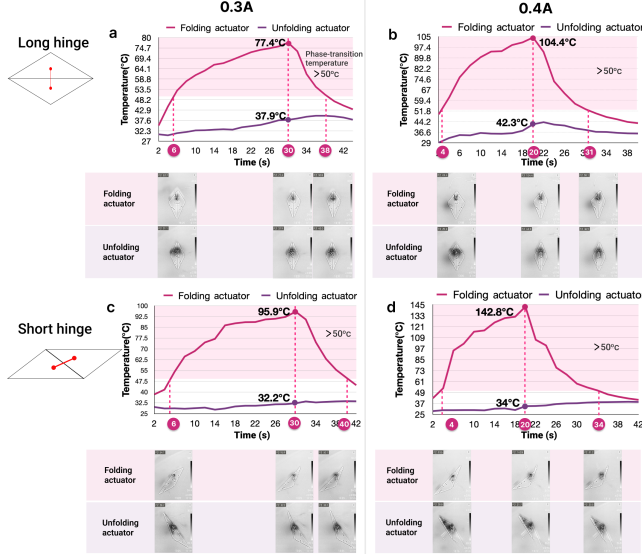


Figure 7: Thermal response of fold and unfold actuators at 0.3 A and 0.4 A. Across conditions, the active side heats rapidly while cross-talk to the inactive side remains limited, supporting alternating actuation with a recovery interval.

4.3 Structure-Level Coupling: Single Active Cells

We then examined how a single active unit cell behaves when embedded in larger passive structures. In each configuration, only the red-marked hinge within the target unit cell was actuated; all surrounding hinges remained passive. As the number of directly connected passive neighbors (S_n in Fig. 8a) increased, the terminal fold angle increased for both cell types, indicating stronger structural constraint from neighboring panels. By contrast, when the number of connected edges remained constant but the overall surrounding passive area changed, we did not observe an equally strong monotonic trend. This suggests that local connectivity is a more important predictor of fold depth than the total size of the surrounding passive region. In practice, users should expect more constrained motion when an active cell is highly embedded in the tessellation, especially when it is surrounded by multiple directly connected passive neighbors (Fig. 8a).

4.4 Multi-Cell Actuation in Linear Structures

Finally, we evaluated five-cell linear structures with up to four consecutive active cells in both horizontal and vertical orientations. Across the horizontal configurations, and in most vertical configurations, the first active cell tended to reach a smaller terminal

fold angle as more cells were activated simultaneously; the vertical collapsing pattern was the main exception. More generally, longer active regions produced non-uniform fold angles across the chain, with interior cells often remaining shallower than end cells, suggesting the effect of boundary-dependent mechanical coupling. When uniform motion matters, users should split long regions into multiple independently driven motion regions or accept non-uniform fold depth across the chain (Fig. 8b).

4.5 Summary of Design Implications

The technical characterization yields three practical recommendations for users. First, discrete speed presets are more useful than continuous current values because the operating envelope is better expressed as a small set of robust actuation regimes. Second, users should maintain a sufficient fold-unfold interval to allow thermal recovery and preserve actuator independence. Third, motion regions should remain short when uniform deformation matters, because both structural embedding and multi-cell coupling reduce fold depth. Table 2 summarizes these recommendations as concrete design choices.

More broadly, the characterization suggests that MetaCanvas should not be understood as a precision actuator array that produces identical cell-by-cell output. Instead, it is a reusable design substrate whose behavior emerges from the interaction among local actuation, structural coupling, and user-defined motion regions.

5 User Workflow

MetaCanvas uses a three-stage hybrid workflow: users explore shapes and motion regions and export guides digitally, then cut and configure the canvas and tune motion on the physical artifact (Fig. 9).

5.1 Define Shape and Candidate Motion Regions

Users begin in the Design and Simulation Interface by defining a target outline, either by sketching on the tessellated grid or importing a reference image and refining the generated outline with local add/delete operations. They then assign candidate motion regions and compare alternatives using an *approximate* folding preview. We emphasize *approximate* because the preview is intended as a design aid for exploring motion placement and overall transformation, rather than as a high-fidelity physical simulator. Once users select a design, the interface exports an SVG with the cut outline and circuit assignment (Fig. 9a3). The interface also includes an optional component library for attaching additional linear motion elements. Each component corresponds to one of the linear motion primitives characterized in Sec. 6.1 (circle, collapsing, and spiral). Users attach a selected component to a boundary of the main shape and adjust its parameters interactively; the interface then updates the global folding preview together with the exported cut and circuit schematics, which users follow during fabrication. We treat this as an advanced extension rather than a required step: users can complete the core workflow without it and introduce it later when exploring a broader motion vocabulary. Note that the circle component here shares the same underlying pattern as the standard “circle” configuration in Sec. 4.4, but is modified to expose more open edges so that it can attach to the irregular, unpredictable boundaries left by cut-outs on the canvas.

Table 2: Design recommendations derived from the technical characterization. Exact actuation duration depends on the selected speed preset.

Design goal	Recommended region	Speed	Actuation	Recommended recovery interval	Rationale
Maximize local fold depth	Single cells or short regions; avoid highly embedded cells	Med./High	5–10 s	≥ 10 s	Fewer passive neighbors usually allow deeper folding.
Maintain uniform motion	Keep regions to 1–3 active cells; split longer regions	Medium	5–10 s	≥ 10 s	Long regions fold unevenly, especially at the ends.
Create fast visible motion	1–2 active cells or short regions	Med./High	Short–med.	≥ 10 s	Higher current speeds folding; short regions respond more reliably.
Compose sequential behavior	Multiple short regions instead of one long region	Medium	Region-specific	≥ 10 s / region	Separate regions support staggered timing with less coupling.

5.2 Cut and Configure the Active Canvas

Users next translate the exported design onto the reusable physical canvas. They cut the pre-instrumented tessellation sheet along the exported SVG outline and activate selected hinges by sliding actuators to the hinge midpoint along the folds specified by the circuit assignment (Fig. 9c). Because actuation and conductive routing are already embedded in the sheet, this phase locally revises cut geometry and motion regions without requiring a new canvas build. Iteration therefore happens through local trimming, repair or reattachment, hinge selection, and retuning rather than rebuilding from discrete modules.

5.3 Tune Temporal Behavior After Fabrication

After physical configuration, users connect each motion region to a Motion Setup Case and tune temporal behavior directly on the fabricated artifact. The case exposes discrete settings for motion order, speed preset, actuation duration, repetition count, and the interval between folding and unfolding. Multiple cases can be used when different regions require independent driving settings. This post-fabrication stage is important because it moves a substantial part of iteration from re-fabrication to retuning. Users can refine synchronization, pacing, and emphasis *in situ* while observing the real artifact, which supports quick comparison of alternative motion sequences without returning to fabrication.

6 Motion Primitives and Demonstrations

6.1 Motion Primitives and Composition Dimensions

Rather than organizing the design space around final folded forms, we characterize it in terms of four design variables that users can specify during cut-and-configure authoring. First, *tessellation family* (e.g., Yoshimura or Kresling) shapes the structural character of motion. Second, *motion primitive* defines the local deformation pattern (Fig. 10a): circle refers to a circular-bending chain, collapsing to inward contraction, and spiral to a progressive twist. Third, *spatial composition* determines whether motion is configured as a single region or as a hybrid combination of multiple regions within one artifact (Fig. 10b). Fourth, *temporal coordination* determines whether regions move synchronously or under independent timing control. MetaCanvas complements passive paper origami by supporting motion placement, grouping, and sequencing on an active substrate.

Table 3: Comparison of motion spaces and their design properties.

	Butterfly	Frog	Fox	Mask	Flower
Tessellation	Yoshi.	Yoshi.	Kres.	Kres.	Yoshi.
Primitive	Spiral	Spiral+coll.	Circle+coll.	Circle/Spiral	Circle+coll.
Spatial comp.	✓	✓	✓	✓	✓
Temporal coord.	–	✓	✓	–	✓

The technical characterization in Sec. 4 provides the empirical constraints that shape this space. Highly embedded active cells fold more shallowly than less constrained ones, and long active chains tend to produce non-uniform fold depth, especially near their ends. Users can therefore either split a long intended motion into multiple independently driven regions when uniformity matters, or they can intentionally use non-uniform folding as part of the visual effect. Fig. 10 is intended as a design aid rather than a complete taxonomy of origami motion: it identifies the motion structures that MetaCanvas currently supports and the practical constraints that matter when composing them.

6.2 Demonstrations

We use five artifacts to probe this design space (see Table 3) rather than to claim fully realized end-use applications. Collectively, they show how the toolkit supports multi-region composition, replaceable expressive modules, and graded peripheral notification.

Animal-like motion. The butterfly (Fig. 11a), frog (Fig. 11b), and fox (Fig. 11c) demonstrate three temporal compositions of multi-region motion. The butterfly uses synchronous activation across four wing regions to produce a flapping motion. The frog staggers hindlimb and forelimb actuation to create a leap-like sequence. The fox separates the tail, feet, and ears into independently timed regions, showing how one artifact can host multiple motion rhythms at once.

Wearable expression concept. The mask (Fig. 11d and 11e) is a concept demonstration of wearable expression with replaceable side modules. The base frame remains stable on the face, while the interchangeable appendages provide different motion forms and emotional meanings: spiral motion suggests tension, whereas circular motion suggests joy. In this demonstration, the actuated side modules are positioned away from direct skin contact; a future face-worn implementation would additionally require insulation or encapsulation, thermal separation, current and duration limits, and fail-safe control.

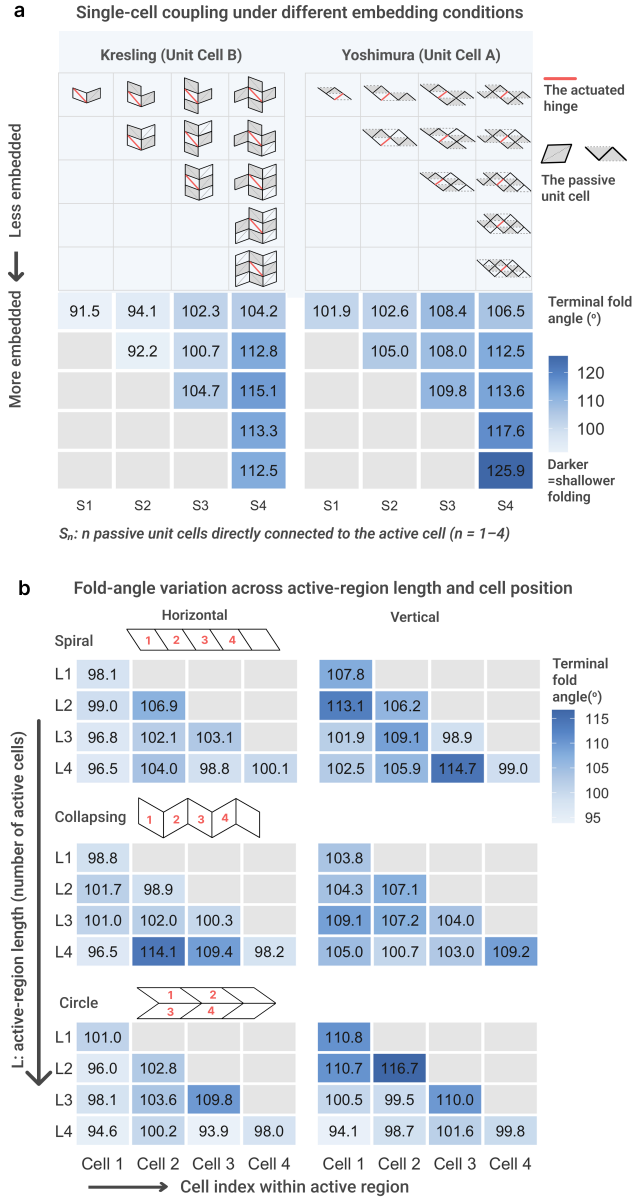


Figure 8: Structural coupling constrains fold depth. (a) Single-cell tests under different embedding conditions. Red marks the actuated hinge; rows vary the number of directly connected passive unit cells (S), and the numbers report the single-cell's corresponding terminal fold angles. (b) As active regions lengthen, fold angles become more non-uniform across the chain. Darker blue indicates larger terminal fold angles (i.e., shallower folding).

Ambient notification. The flower artifact (Fig. 11f) illustrates how motion composition can encode the water-stress level of a monitored plant. As the plant becomes drier, more flowers deform, allowing the number of moving elements to represent the severity of the condition. We present this as a concept demonstration of

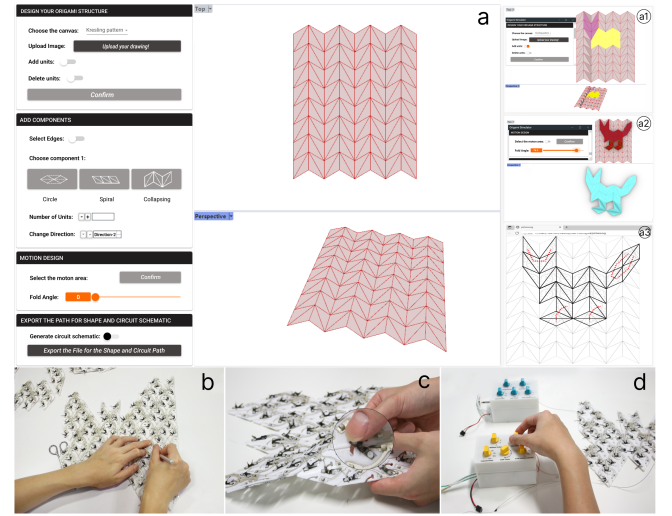


Figure 9: MetaCanvas cut-and-configure workflow. (a1–a3) Users define an outline, assign motion regions, preview approximate deformation, and export the cut outline and circuit assignment. (b) Users cut the reusable active canvas. (c) Users activate selected hinges by sliding actuators to the hinge midpoint. (d) Users tune temporal parameters with the Motion Setup Case.

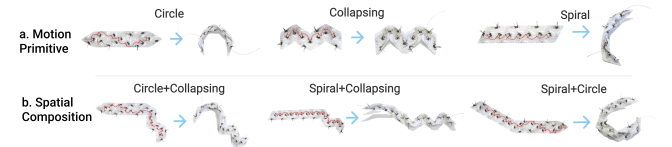


Figure 10: Motion space supported by MetaCanvas. Top: three motion primitives—circle, collapsing, and spiral—derived from the two tessellation families. Bottom: example spatial compositions formed by combining primitives within one artifact.

using distributed shape change to communicate gradual changes in plant state, rather than as a fully integrated sensing system.

Taken together, these artifacts show that MetaCanvas supports reusable motion composition across animal-like motion, wearable expression, and ambient notification. More importantly, they show that the contribution is not a fixed set of application forms, but a reusable substrate that can be cut, configured, and retuned across multiple motion scenarios.

7 Design Study

7.1 Participants and Procedure

To understand how first-time users learn, appropriate, and revise MetaCanvas, we conducted an exploratory design study with 12 participants. Rather than benchmarking MetaCanvas against another toolkit, the study examined three questions: (1) how readily users could understand the cut-and-configure workflow after brief onboarding, (2) how they responded to fabrication mistakes during physical construction, and (3) how they used post-fabrication motion tuning to explore distinct alternative motion behaviors.

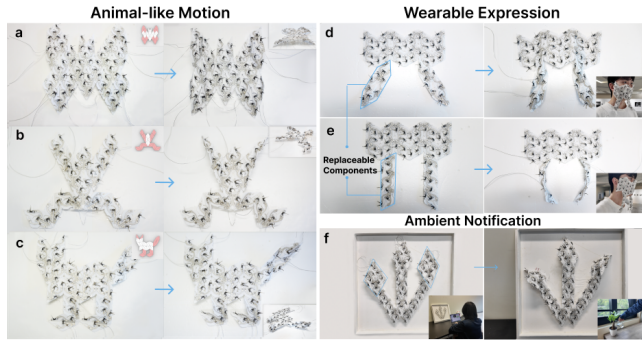


Figure 11: Five demonstrations: (a) butterfly with synchronous wing actuation; (b) frog with temporally coordinated forelimb and hindlimb motion; (c) fox with independently timed motions of the tail, feet, and ears; (d, e) wearable-expression concept with replaceable side modules; and (f) flower-like ambient display with graded peripheral motion.

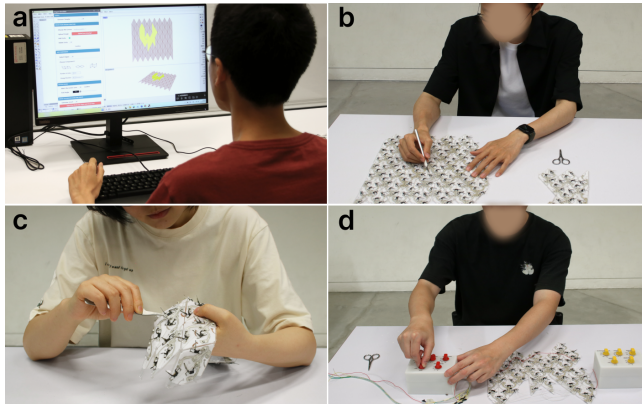


Figure 12: Design-study procedure: (a) digital design, (b) canvas cutting, (c) hinge activation and circuit connection, and (d) temporal tuning with the Motion Setup Case.

To address these questions, we combined a guided first-use task with an open-ended design task (Fig. 12).

We recruited 12 participants (4 women; age: $M = 27.7$, $SD = 2.19$) with backgrounds in computer science ($n = 3$), electronic engineering ($n = 3$), industrial design ($n = 4$), and digital interface design ($n = 2$). Table 4 details each participant’s self-reported experience with computer-aided design (CAD), origami, and physical computing. To reduce first-use confusion, participants watched two preparatory videos 1–2 days beforehand that introduced the workflow, example artifacts, and motion settings. At the beginning of the session, the facilitator gave a 15-minute walkthrough of the Design and Simulation Interface and answered clarification questions. During the study, the facilitator intervened only when participants were blocked.

The study consisted of two stages. In Stage One (30 minutes), participants created a rabbit-head artifact with moving ears, starting either from a provided image or from their own sketch. This ensured that all participants experienced the full workflow—digital design and ideation, cutting, circuit connection, and motion tuning—during

first use. In Stage Two (60 minutes), participants designed an original shape-changing artifact using the same workflow. This open-ended task foregrounded ideation and exploration rather than task completion alone. After Stage One, participants completed a background questionnaire and a NASA-TLX survey. After Stage Two, they completed a second NASA-TLX survey, a usability questionnaire (UEQ) [25], and a creativity questionnaire inspired by prior creativity scales [4], followed by a 20–30 minute semi-structured interview about their workflow experience, design decisions, perceived limitations, and possible application areas.

7.2 Data Collection and Analysis

We collected three types of data. First, we video-recorded all sessions and annotated the time spent in digital design, cutting, circuit connection, and motion tuning. Second, we audio-recorded and transcribed the post-study interviews. Two researchers reviewed the transcripts iteratively and consolidated recurring themes through thematic analysis [3]. Third, we collected questionnaire data on prior experience, perceived workload, usability, and creativity. Because the study was exploratory and involved a small sample, we report questionnaire results descriptively rather than as confirmatory evidence.

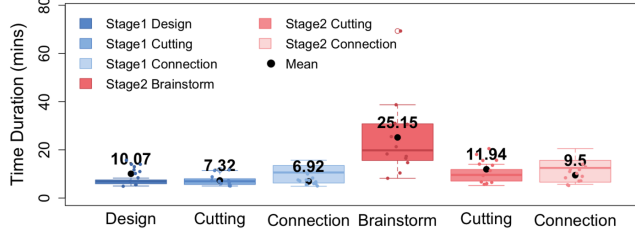
7.3 Results

Workflow progression and time distribution. Participants generally progressed through the workflow sequentially, with few cross-phase interruptions. The phases annotated in Fig. 13 fall into the two authoring domains introduced in Sec. 5: Design (Stage One) and Brainstorm (Stage Two) are digital phases carried out in the Design and Simulation Interface, whereas Cutting and Circuit Connection are physical phases carried out on the canvas and the fabricated artifact. Stage One took an average of 26.3 minutes ($SD = 5.52$). Within this stage, digital design accounted for a mean of 10.07 minutes, while cutting and circuit connection occupied the remaining time in roughly comparable proportions. Stage Two took an average of 47.73 minutes ($SD = 15.33$; Fig. 13), about 21 minutes longer than Stage One, and the increase came mainly from digital work: brainstorming and revising designs in the interface averaged 25.15 minutes, compared with 10.07 minutes in Stage One. This gap reflects Stage Two’s broader digital scope: ideating and iterating over candidate shapes and motion regions before committing to cuts. Overall, this distribution reflects a hybrid workflow: software supports shape and motion-region exploration, while cutting, circuit connection, temporal tuning, repair, and reinterpretation (Sec. 7.4) take place on the physical artifact. Questions arose primarily during digital design, especially when participants explored the optional component library, whereas cutting, circuit connection, and motion tuning typically required little assistance. Once motion regions had been defined, participants generally needed only a few seconds to set temporal parameters on the Motion Setup Case.

Perceived workload, usability, and creativity. Participants reported low temporal demand across the two stages ($M = 2.2$, $SD = 1.69$) and moderate effort (Stage One: $M = 3.8$, $SD = 1.23$; Stage Two: $M = 3.8$, $SD = 1.40$), while also reporting high confidence in their ability to complete the tasks successfully (Stage One: $M = 6.0$, $SD = 0.47$; Stage Two: $M = 5.4$, $SD = 0.70$).

Table 4: Self-reported prior experience by participant (N = None, L = Little, M = Moderate, E = Extensive).

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
CAD	L	M	L	E	N	N	L	M	L	N	L	N
Origami	L	L	L	M	L	L	M	L	L	L	M	L
Physical computing	E	E	E	M	L	N	M	L	E	M	L	N


Figure 13: Time spent in each phase of the design study. Design (Stage One) and Brainstorm (Stage Two) are digital; Cutting and Circuit Connection are physical.

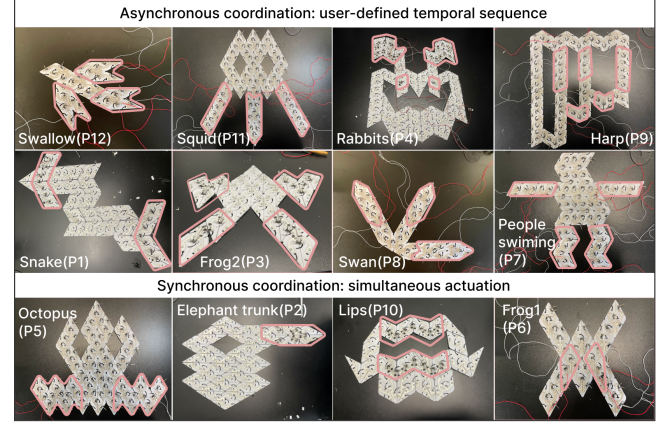
Post-study ratings further suggested that MetaCanvas was easy to learn ($M = 6.08$, $SD = 0.67$), visually appealing ($M = 6.33$, $SD = 0.65$), and supportive of an efficient design process ($M = 5.83$, $SD = 0.83$). Participants also reported that the toolkit supported flexible modification and risk-taking during design (risk comfort: $M = 5.5$, $SD = 1.00$; flexible modification: $M = 5.75$, $SD = 0.62$). Complete questionnaire results are reported in Appendix D.

Design outcomes and repair. Stage Two artifacts spanned animal-inspired motion and expressive object-based forms (Fig. 14). Many participants gravitated toward animal metaphors, which they described as intuitive sources of motion ideas, while others explored forms such as a harp (P9) and lips (P10). Given the single-session, first-use setting, we cannot determine whether this concentration reflects a persistent limitation in expressive range. It may reflect priming from the preceding rabbit-head task, reliance on familiar animal forms, and the toolkit’s support for short, local motion regions that readily map to appendage-like movement. Consistent with the possibility that participants’ ideas might broaden with greater familiarity, P4 and P11 noted in the post-study interviews that they would like to explore wearable prototypes after gaining more experience with the toolkit. Several participants also encountered minor fabrication errors, most commonly over-cutting. Instead of discarding the artifact, they repaired missing regions with TPU tape or reinterpreted the partially cut form as a viable variation. These episodes are important because they show that iteration sometimes continued through repair or reinterpretation rather than full re-fabrication.

7.4 Findings

The core workflow was approachable after brief onboarding.

After the pre-session videos and in-session walkthrough, participants asked relatively few questions outside the digital design phase, and most completed both tasks independently. P11 summarized this learning curve: “I found it easy to use, and I know how to use it once I see the toolkit and the design pipeline.” Several participants emphasized that they did not need deep prior knowledge of origami


Figure 14: All 12 final artifacts from the open-ended design task (one per participant), grouped by temporal coordination: synchronous (multiple motion regions actuate simultaneously) vs. asynchronous (regions actuate in a user-defined temporal sequence). Red frames mark selected motion regions.

or circuitry. As P5 put it, “I don’t need to know knowledge such as origami or circuit; it has no requirement for related skills.” The interface preview helped them anticipate how a design would behave after fabrication. However, P2 pointed out that locating the correct cut positions on the 8×8 canvas could be visually demanding because the 64 unit cells made it easy to lose track of the target region.

MetaCanvas supported repair and reinterpretation during fabrication. Because unit cells are connected through TPU-tape hinges, participants could recover from local cutting mistakes by reattaching removed regions instead of rebuilding the entire artifact. For example, P4 accidentally removed three tessellation units that were intended to remain in the structure but repaired the error by reattaching the missing sections with TPU tape. More interestingly, some participants reinterpreted unexpected cut results as design opportunities (e.g., P1, P5, P10). P5 initially attempted to create a lotus flower. After realizing that the cut size was larger than expected, she trimmed additional tessellation units beyond the motion region and remarked, “It looks like an octopus, interesting.” She then finalized the design as an octopus. Similarly, P10 designed moving lips inspired by the “Howler” in *Harry Potter*. Although she mistakenly removed extra tessellation units from the upper lip, she chose to continue after noting that the overall figure still resembled lips in an abstract form. This was likely because the repeated tessellation acted as a coarse, pixel-like substrate that abstracted the resulting shapes, making them open to multiple plausible interpretations rather than being read simply as errors.

The Motion Setup Case enabled in situ exploration of temporal behavior. Participants described the Motion Setup Case as intuitive and satisfying to use. By separating motion tuning from the computer interface, the case let them adjust pacing, order, and repetition while directly observing the fabricated artifact. Several participants (P3, P5, P9, P11, P12) also valued the tangible knob interaction, noting that they could make quick adjustments through touch while focusing visually on the moving structure. As P2 explained, *“I can directly interact with the case, since I see the real-time feedback from the display. With the haptic feedback, I just turn the knob without looking at parameters—just by feeling. This is really interesting.”* In addition, both P9 and P10 emphasized that embedding motion parameter settings directly into the case reduced debugging complexity and made it easier to experiment with more sophisticated motion sequences.

The interface’s optional component library showed promise but was less approachable on first use. The library broadened the motion vocabulary, but only P8 and P12 used it successfully in a single session. Others (P1, P4, P6, P9, P11) expressed interest in revisiting it after gaining familiarity with the basic workflow. This suggests that the core cut-and-configure process is accessible on first use, whereas richer compositional features may require repeated exposure or stronger interface scaffolding.

8 Discussion, Limitations, and Future Work

8.1 Repairability and Reinterpretation Support Continued Iteration

A central contribution of MetaCanvas is not merely that users can cut a tessellated sheet, but that they can continue iterating after cutting. In conventional subtractive workflows, mis-cuts often terminate an iteration or force complete re-fabrication [30, 38, 55]. In our study, participants instead repaired local damage with TPU tape or reinterpreted altered shapes as new design variants. This suggests that repairability and abstraction can work together: removable hinges make local correction practical, while the repeated tessellation helps imperfect results remain visually coherent. We therefore see error tolerance not as a peripheral convenience, but as a design property that changes the tempo and mindset of creative exploration [42, 43]. Although this property may also reduce material waste, we did not measure environmental impact directly; we therefore frame sustainability as a possible implication rather than a demonstrated outcome.

8.2 Post-Fabrication Tuning Extends Design Iteration Beyond the CAD Stage

MetaCanvas also shifts part of design iteration from pre-fabrication planning to post-fabrication adjustment. The Motion Setup Case lets users refine timing on the physical artifact itself, which is particularly valuable because motion quality depends on structural embedding, region length, and thermal timing, as shown in our technical characterization. For timing changes, the case supports rapid in situ exploration of pacing and synchronization. This matters because timing choices are often hard to judge in the abstract: users need to see whether a region appears too abrupt, too delayed, or out of sync with neighboring motions. More broadly, post-fabrication

iteration remains hybrid: evaluating the artifact may prompt a return to the digital interface for substantial changes to geometry or circuit routing, while regrouping regions may require physical reconnection.

8.3 Current Limitations and Future Directions

Our results should be interpreted in light of several limitations. First, the study was exploratory and non-comparative. With 12 participants and no baseline toolkit, the questionnaire results should be read as supporting context rather than as strong evidence of superiority. Second, performance remains affected by fabrication variability, including SMA properties, printing tolerances, manual actuator construction, and hand assembly of the canvases. These factors can produce different motion behavior even across nominally identical regions. Third, the 8×8 canvas remains visually dense and time-consuming to prepare: locating specific cells during cutting and configuration takes attention, and starting from a fresh substrate is still slow. Fourth, the current hardware still exposes practical constraints, including visible wiring, hot SMA elements, an approximately 10 s thermal recovery interval between fold and unfold, and the need for multiple Motion Setup Cases when several regions require independent control.

These limitations point to several directions for future work. A more standardized production pipeline and tighter physical simulation could improve the predictability of fold angle and timing. Insulation or encapsulation, thermal separation, active cooling, current and duration limits, fail-safe control, compact connectors, and more integrated routing are needed before wearable or everyday use. On the software side, the interface could better support multi-region sequencing and richer motion composition, especially through the optional component library. Comparative studies with modular assembly toolkits would also help isolate the specific benefits of the cut-and-configure workflow. Finally, longitudinal studies would help reveal how users’ strategies evolve with repeated use and whether advanced features become more meaningful once the core workflow is familiar.

8.4 Future Technological Vision

Beyond these refinements, we frame MetaCanvas as an early step toward treating shape-changing interfaces as an active raw material: a pre-instrumented sheet whose geometry, active regions, and temporal behavior remain authorable through cutting, hinge selection, and retuning. Concretely, we target programmable, distributed shape-changing sheets: lightweight surfaces whose local deformation primitives can be cut, grouped, sequenced, and reused—for ambient displays, expressive product skins and wearable modules in line with SMA-actuated shape-changing textiles [16, 49], and reconfigurable robotic surfaces related to repeated-cell dynamic materials [5, 39]. The current performance envelope reflects both the tessellation structure and its SMA/carbon-fiber implementation. High-rate SMA driving and improved heat transfer can reduce response and recovery times [8, 31], while 4D-printed shape-memory-polymer hinges and spatially programmed liquid-crystal elastomers point to more integrated and locally differentiated actuation [24, 51, 52].

Dielectric elastomers provide a complementary route to fast, large-strain sheet motion [40]. These technologies are not drop-in replacements—their drive, electrode, thermal, and fabrication requirements would require redesign—but they identify concrete paths toward faster, safer, and more spatially addressable active raw materials while retaining the cut-and-configure authoring principle.

9 Conclusion

We presented MetaCanvas, a reusable prototyping toolkit for tessellation-based shape-changing structures. MetaCanvas combines a pre-instrumented active canvas, a design interface for defining cut outlines and motion regions, and a tangible controller for post-fabrication motion tuning. Our technical characterization established practical operating constraints for speed, timing, and motion-region length; our demonstrations illustrated a range of motion compositions; and our design study showed that participants could learn the workflow after brief onboarding, repair or reinterpret local fabrication mistakes, and continue exploring temporal behavior on the same physical artifact. Together, these results suggest that reusable active substrates can shift shape-changing prototyping from one-off fabrication toward iterative workflows of cutting, configuring, and retuning.

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A Conductive-Trace Fabrication and Resistance

Based on the triangle geometry, we designed a curved conductive trace with a width of 1.6 mm. During circuit fabrication, conductive silver paint (HumiSeal 948-06G) was applied to the 3D-printed triangles (Fig. 15a). To balance low resistance with fabrication effort, each trace received one to five coats. After each coat dried, we measured the resistance between the two ends of the trace. As shown in Fig. 15c, resistance decreased as the number of coats increased but plateaued after the third coat, dropping only from 2.29 Ω after the third coat to 1.90 Ω after the fifth. The corresponding SDs ranged from 0.39 Ω to 0.43 Ω . We therefore used three coats for all tessellation units in MetaCanvas.

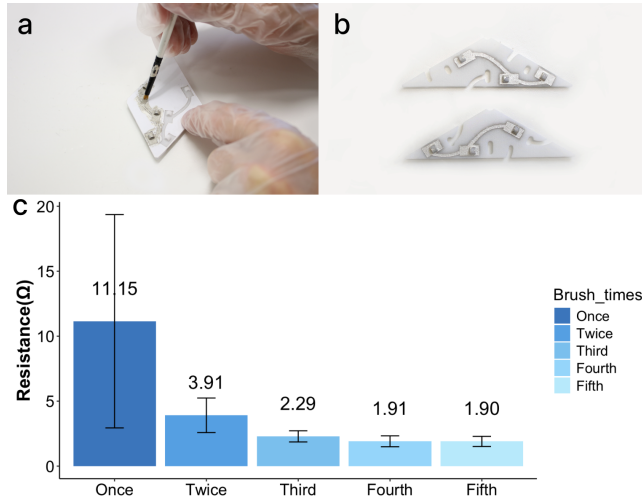


Figure 15: Conductive-trace fabrication and resistance. (a) Conductive silver paint applied to the triangle surface. (b) Actuator lead and connection geometry. (c) Resistance of conductive traces as a function of coating count.

B Actuator and Linear-Circuit Resistance

For actuator fabrication, a 2-mm-wide carbon-fiber heater was wrapped three times around the working section of the SMA sheet to ensure complete coverage of the SMA surface. The 7-mm-long heater lead (Fig. 16) was passed through the buckle and connected to the conductive trace on the triangle. To reduce lead resistance and avoid unnecessary heating, we coated the lead with conductive silver paint. We measured 10 samples of each of the four actuator variants (Fig. 16); mean resistance across the four types ranged from 5.27 Ω to 6.06 Ω .

We also measured the total resistance of representative linear circuit configurations (Fig. 17).

C Preliminary Actuator-Selection Study

Before the main technical characterization, we conducted a preliminary study to select the actuator training angle and operating current range. We evaluated 1.5-mm-thick triangles at currents from 0.20 A to 0.50 A and SMA sheets with trained angles of 30°, 45°, 60°, 90°, and 120°. Under the 30°-trained SMA condition (Fig. 18), complete folding duration decreased from 72.2 s to 9.4 s for the

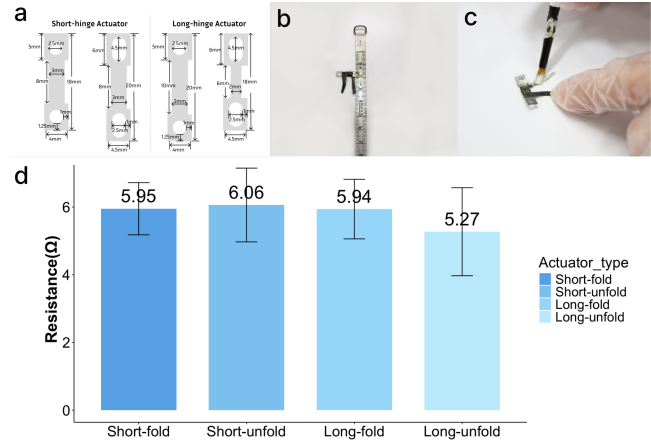


Figure 16: Actuator fabrication and resistance. (a) Four actuator variants. (b) A fabricated actuator. (c) Conductive silver paint applied to the heater lead. (d) Resistance of the four actuator variants.

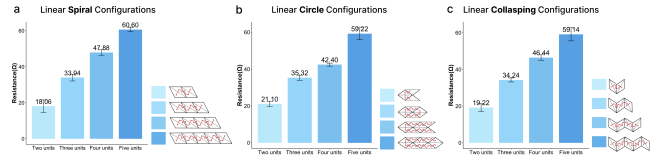


Figure 17: Total circuit resistance of representative linear spiral, circle, and collapsing configurations with two to five connected units.

long hinge and from 80.0 s to 14.5 s for the short hinge as current increased from 0.20 A to 0.50 A. We also compared fold-accuracy ratios across trained angles at 0.40 A. We defined the fold-accuracy ratio as $R_{\text{fold}} = (180^\circ - \theta_{\text{term}}) / (180^\circ - \theta_{\text{train}})$, where θ_{term} is the measured terminal fold angle defined in Sec. 4 and θ_{train} is the SMA training angle, which defines the target terminal angle. Across the tested conditions, the 60° training angle provided the best overall trade-off between speed and accuracy and was therefore used in the main characterization. These results also informed the 0.25–0.45 A range used in the main characterization.

Representative fold-unfold sequences. To complement the mechanism described in Sec. 3.2, Fig. 19 shows representative single-cycle fold-unfold sequences for Unit Cells A and B under the selected actuator configuration. In each sequence, the antagonistic fold and unfold actuators were energized alternately, driving the same hinge in opposite directions; the visible mounting arrangement is reversed between the two cell geometries. These sequences are qualitative examples rather than aggregate timing measurements; quantitative results for folding duration, terminal fold angle, and thermal recovery are reported in Secs. 4.1 and 4.2.

D Quantitative Results of the User Study

This appendix reports item-level descriptive statistics for the questionnaires used in the design study. Given the exploratory study and small sample, Tables 5–7 provide medians and interquartile ranges

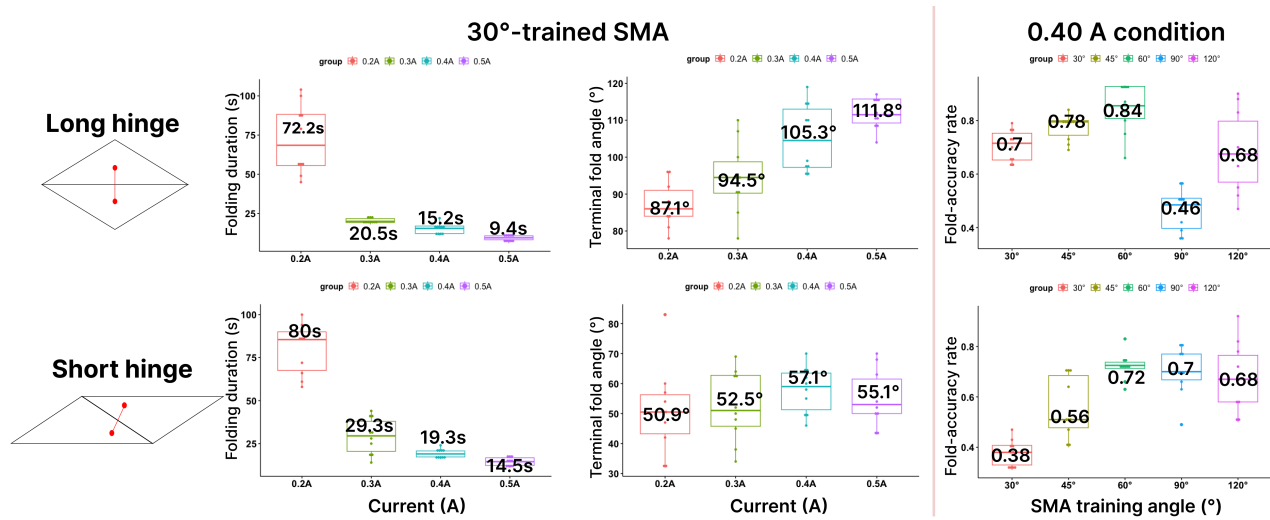


Figure 18: Preliminary actuator-selection results. Left and center: folding duration and terminal fold angle for long and short hinges using 30°-trained SMA across 0.20–0.50 A. Right: fold-accuracy ratio across SMA training angles at 0.40 A.

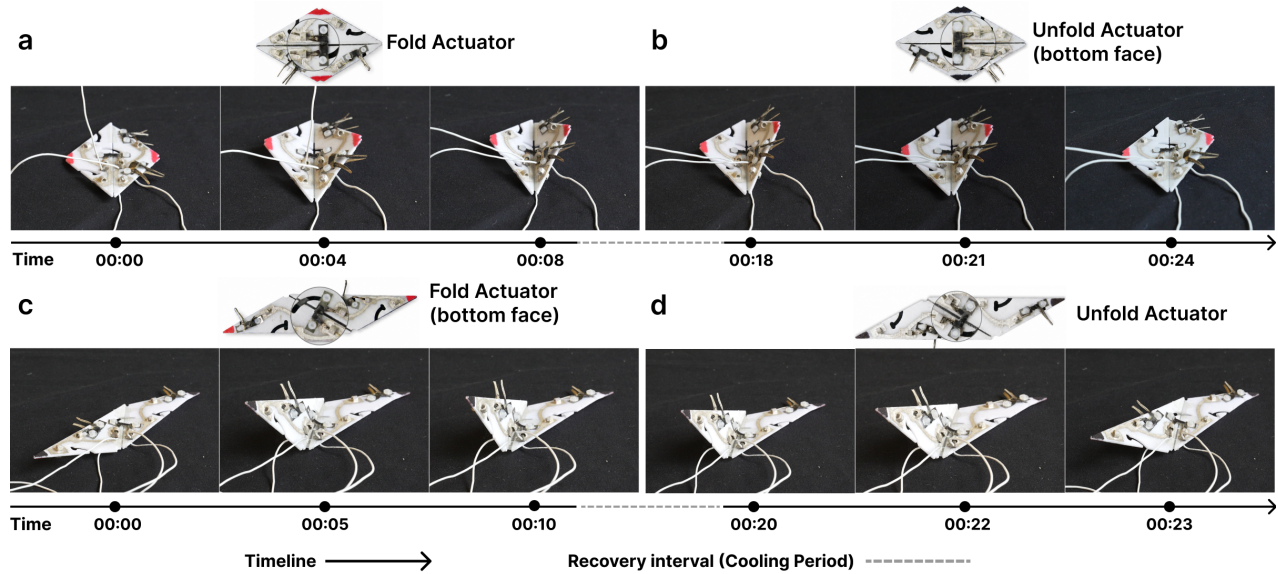


Figure 19: Representative fold–recover–unfold sequences for Unit Cells A and B under the selected actuator configuration. (a, b) Unit Cell A during fold and unfold actuation, respectively. (c, d) Unit Cell B during fold and unfold actuation, respectively. Dashed segments indicate the recovery interval between antagonistic actuations.

(IQRs) for the creativity-related, usability-related, and NASA-TLX items, respectively.

Table 5: Medians and interquartile ranges (IQRs) for creativity-related questionnaire items.

Item	Median	IQR
Originality (My design is original)	6	1.25
Flexibility (I can shift my approach and generate new ideas when the current ones aren't working)	6	1.00
Complexity (My design includes a variety of motion elements)	5	2.25
Design Outcome (I believe my design solution is of high quality)	5	0.50
Novelty (I feel that my design solution offers something novel and innovative)	6	1.00
Risk Taking (I feel comfortable taking risks to create something unconventional)	6	1.00

Table 6: Medians and interquartile ranges (IQRs) for usability-related questionnaire items.

Item	Median	IQR
Attractiveness (The system is attractive)	6	1.00
Perspicuity (I quickly learned how to use the system)	6	0.25
Efficiency (The system helps me to achieve my goals quickly)	6	1.25
Dependability (The system behaves as expected)	6	0.50
Stimulation (The system is fun to use)	6	2.00
Novelty (The system offers new possibilities)	7	1.00

Table 7: Medians and interquartile ranges (IQRs) for NASA-TLX items across the two study stages.

Item	Stage One		Stage Two	
	Median	IQR	Median	IQR
Mental Demand (How mentally demanding was the task?)	3	0.75	3	1.75
Physical Demand (How physically demanding was the task?)	3	1.50	3.5	1.75
Temporal Demand (How hurried or rushed was the pace of the task?)	2	1.75	2	1.75
Performance (How successful were you in accomplishing what you were asked to do?)	6	0.00	5	0.75
Effort (How hard did you have to work to accomplish your level of performance?)	3.5	1.75	3.5	2.00
Frustration (How insecure, discouraged, irritated, stressed, and annoyed were you?)	2	1.00	1	2.00