MiuraKit: A Modular Hands-On Construction Kit For Pneumatic Shape-Changing And Robotic Interfaces

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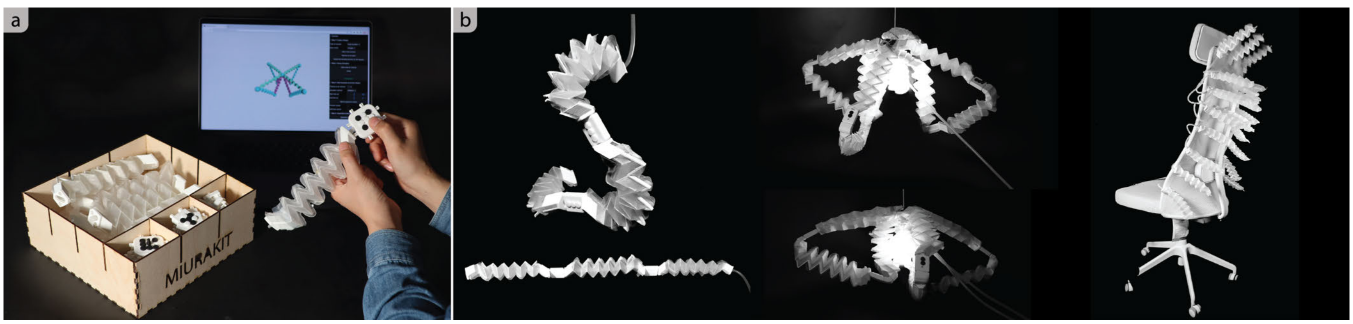

Figure 1: We present (a) MiuraKit, a hands-on construction kit for pneumatically actuated shape-changing interfaces. It consists of generic Miura-ori-based actuators, of novel, manually configurable connectors, and of a design tool supporting complex designs. These few parts enable (b) a range of applications, including a snake-like robot, a shape-changing lamp, or a creature-like chair.

ABSTRACT

Building shape-changing, robotic or deployable interfaces is notoriously difficult, often requiring fabrication skills or specialized hardware. We present a construction kit for novice users to enable immediate hands-on exploration of custom shape-changing or robotic structures through pneumatically actuated origami tubes. Our construction kit consists of generic origami actuators that can be combined with our connectors to result in a variety of shapes and motions. Our novel connectors support simple mechanical connections through snap fits and pneumatic configurations through plugs. To assist users in designing and previewing complex deformations, we provide a design tool that generates control code for user-defined designs. We envision that our construction kit will facilitate creativity support tasks (e.g. product design) or education. We demonstrate the capabilities of our construction kit with three application examples and a series of objects created during our co-creation study with novice users.

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CCS CONCEPTS

• **Human-centered computing**;

KEYWORDS

Construction kit, Soft robotics, Shape changing interfaces, Pneumatics, Design, Education

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1 INTRODUCTION

Dynamic interfaces are highly expressive, but hard to build for novice users. We consider dynamic interfaces to include shape-changing interfaces, which are popular because they can convey dynamic affordances [15, 17] or physically manifest digital contents [9, 32, 38]; deployable structures, which can unfold into predefined shapes based on simple actuation [26, 49]; or soft robots [5, 20, 43].

These interfaces need actuation. Some systems use motors [9, 17] or active materials [53, 57], but many use pneumatic actuation [38, 45, 49, 56] because the hardware is readily accessible, it provides fast and powerful actuation while allowing the shape-changing end-effectors to be soft and safe for interaction. However, such airtight systems are hard to build and to control for novice users. Recent research aims to support users in building such pneumatic systems but either require users to fabricate the airtight actuators themselves [16, 52, 58], which is notoriously difficult, or the systems propose specialized hardware [38, 45, 49] that is not available to users.

In this paper, we propose a construction kit that supports *immediate hands-on* exploring and prototyping of custom pneumatically actuated shape changing and robotic interfaces. While designing our research prototype, we envision the simplicity of Lego with the power of shape-changing interfaces. We summarize our *design goals* in the following:

- G1. *No fabrication required.* Users are not required to fabricate any parts, the construction kit contains everything that is necessary to build and run shape-changing prototypes.
- G2. *Reusable and reconfigurable.* The parts of the construction kit can be disassembled and reassembled into different interfaces.
- G3. *Hands-on configuration.* The construction kit supports hands-on configuration of spatial arrangement (i.e., the geometry of the interface) and of the air groups (i.e., trigger the shape change).
- G4. *Assisting design of complex shapes.* Complementary to the hands-on design, the kit should support users in creating more complex designs with digital design, simulation, and control code.

In the following, we give an overview of the construction kit we developed guided by our design goals.

1.1 Overview of MiuraKit

To implement our design goals, we developed our construction kit (Figure 1) to consist of (1) generic pneumatic actuators, such that users do not need to fabricate parts, (2) simple manually configurable connectors, and (3) design software to assist with assembly instructions and control of complex designs. We show our construction kit in Figure 1a and showcase example applications in Figure 1b. Because of the dynamic nature of our interfaces, we refer the reader to our supplemental video which depicts the motion of the actuators.

(1) Generic pneumatic actuators: Since pneumatically actuated soft robots are an active research topic, we reviewed developments in robotics and related engineering fields. We found that origami structures make for an efficient soft actuator that is flexible, tunable, and generic. After replicating and testing several origami structures, we selected the Miura-ori tube as our actuator. They offer the advantages of being easy to actuate to compress or bend and to tile them into different shapes or surfaces. Effectively, it's a versatile structure to minimize the number of parts in our construction kit, yet enable many functions through combination. Since the structure is generic, we design them with mass-fabrication in mind such that we don't burden users with the difficult fabrication of air-tight actuators, implementing our design goal G1.

(2) Manually configurable connectors: The pneumatic Miura-ori tubes need to be arranged into their target shape to implement the shape-changing interface. We provide a simple yet configurable connector with our kit. To lock the Miura tubes mechanically in place, we add snap-fits on the connector (see Figure 1a). The snap-fit designs allow easy assembly and disassembly of the shape, realizing our design goal G2. Additionally, the orientation of actuators can be manipulated by adding adapters of different angles, which implements the mechanical hands-on configuration aspect of G3. The connector has air channels inside which can be configured by users hands-on by inserting silicone plugs to configure the airways through the connector. The connector design supports all possible permutations of air groups, allowing users to experiment hands-on, which implements G3.

(3) Design software: While our construction kit is designed for users to experiment manually with different configurations, we also complement our construction kit with an online design editor. This editor is built to support designing more complex shapes and/or time-dependent pneumatic control. It is easy to access online without installation, and simulates the shape-change and export control code for time-dependent valve control, if desired. This part of our kit implements G4.

1.2 Contributions

In summary, we contribute MiuraKit, a pneumatic construction kit for immediate hands-on exploration of shape-changing interfaces. Specifically, we contribute:

(1) the *design and development of the construction kit* consisting of linear and bending origami actuators, with a series of pneumatic and mechanical connectors,
(2) a *design tool* assisting novice users with complex designs, which includes motion simulation and control code generation,
(3) demonstration of the utility of our construction kit by laying out the *design space* and showcasing multiple *application examples*, and
(4) validating our construction kit and its potential for hands-on design of shape-changing interfaces with a *user study*.

1.3 Broader Impact

Due to its modular design, this work might have a positive impact on the reduction of waste in prototyping. Most 3D printers used in industry are primarily used for rapid prototyping of products [12]. Especially such shape-changing applications, where the mechanism and the effect of the change might be hard to assess, product designers might create many versions that all get tossed when the final design is found. Our kit makes exploration of such dynamic, shape-changing interfaces tangible and easily to explore while remaining reusable. Additionally, distributed product design teams would have to re-print versions to explore the current design's haptic properties.

Additionally, we believe that this construction kit can be beneficial in K-12 education to teach concepts such as geometry or dynamic mechanical properties such as damping and elasticity. Since the kit is reusable and low-cost when mass-manufactured, schools and community centers can use it for playful STEM education.

We acknowledge that if the actuators break, they will produce some plastic waste in the end. We hope to find sustainable, compostable materials that can be used to manufacture the actuators in the future.

2 RELATED WORK

Our work builds on previous work on shape-changing interfaces and soft robotic actuators.

2.1 Shape-Changing Interfaces

Shape-changing interfaces have been investigated using various actuation methods [42, 48], such as fluid-driven [14, 23, 29], electro-hydraulic [41], shape memory alloys [30, 50], tendon [1, 55], and phase change [28, 33]. Meanwhile, the pneumatic actuation method is attractive due to its quick response, large power, and accessible hardware [34, 38, 56, 60]. Specifically, PneUI [56] and Sticky Actuators [35] introduced pneumatically-actuated soft structural composites and elastomers with integrated sensing. PneuMesh [10] explores the pneumatic actuation on piston actuators to form truss structure deformable robotic system.

Recently, Shape-changing toolkits [19] have been explored to enable end-users to build customized artifacts and simplify the design and fabrication process. TEX(alive) explores temporal expressions in shape-changing textile interfaces [25]. Compressables [6] introduced a prototyping toolkit for wearable compression-based haptic feedback. MorpheesPlug [16] provided a parametric design of six primitive 3D-printable shape-changing widgets. To further lower the barrier of creating soft robotics, PneuBots [58] provided a construction starter kit with seven types of self-foldable segments with high tensile strength.

We expand the above systems such as PneuBots by introducing a pneumatic connector that enables flexible air-group configuration of actuators, which can enable users with more hands-on ideation of the dynamic motion of shape-changing objects. Meanwhile, our pneumatic actuators can be disassembled after use and reassembled for temporal interfaces with versatile spatial arrangements compared to TEX(alive). Our construction kit consists of tube-shaped origami actuators with a series of pneumatic and mechanical connectors. The proposed origami actuators are driven by negative pressure with multiple degrees of freedom, and can also be reconfigured to use as passive structures for force feedback or shape morphing [7, 39].

2.2 Soft Robotic Actuators

The adaption of soft robotics principles and actuators into the HCI domain enables more natural user interfaces that leverage the ability to programmatically control physical structures [2, 44]. Soft robotic actuators have shown enormous applications such as interactive devices [24, 31], assistive wearables [45], or haptic feedbacks [61]. For example, Luo et al. [24] present soft pneumatic actuators via machine knitting with sensing abilities for assistive wearables and soft robotics. OmniFiber [14] developed line-like fluidic artificial muscles for movement-based interactions.

Among the soft robotic actuators, origami actuators exhibit inherent compliance through their deployable structures. They can be constructed with rigid materials without losing their shape-morphing capability, bringing soft-rigid hybrid functionalities [13, 46]. Origami tubes are cylinder-shaped structures that can not only act as the robot skeleton but also be used for driving motion in robotic systems, exhibiting diverse robotic behaviors such as locomotion, manipulation, and grasping. Onal et al. [36] laser-machined polymer films to build Yoshimura and Waterbomb tubular structures. Wu et al. [54] introduced magnetically controlled origami robotic arms based on Kresling patterns for multimodal deformations, including stretching, folding, omnidirectional bending, and twisting. Woongbae et al. [18] present dual-morphing stretchable origami with the Miura-ori tube. Kiju et al. [21] present a cable-driven underactuated robotic gripper with the 3D-printed twisted tower origami tube.

We use the Miura-ori tube structure as the generic actuator in our construction kit because it has flexible motion and is easy to actuate. Meanwhile, the geometry of it is easy to be coupled together into a variety of shapes and spatial arrangements.

3 MIURAKIT COMPONENTS

Our MiuraKit consists of 3 main components, i.e., soft actuators, a novel connector that allows users to configure their shape-changing applications hands-on, and an interactive design tool assisting them with complex design and control. We show an overview of our kit in Figure 3.

3.1 Miura-ori Tube Actuators

The soft actuators in our construction kit enable the shape-change of the structure and are based on the Miura-ori pattern. Figure 2 *(top left)* shows how the Miura-ori tube compresses upon the negative air pressure, and bends when we augment it by adhering a simple 3D-printed constraint to its side to increase the stiffness of one side. We offer users these 2 versions of the Miura-ori tube in our kit, which can be used as linear and bending actuators.

These simple deformations enable a large **design space**, as we show in Figure 2. Our tubes can achieve *transformations* across different dimensions. Simple 1D static arrangements can result in 1D or 2D actuated states, as well as in 3D shapes by coupling bending tubes in different directions.

Our tubes can be *coupled* into a variety of spatial arrangements (see Figure 2 *center*). Users can connect the Miura-ori tubes to configure the skeleton or wireframe of their shape-changing geometry. By bundling 2 or 3 Miura tubes together, users can dynamically control the compression and direction of bending. The geometry of the Miura-ori tubes affords tiling them into surfaces that can be actuated as one or partially resulting in organic deformation, as depicted in Figure 2. The free configuration of the tubes naturally enables combinations of skeleton and surface arrangements.

The pneumatic *actuation* of the tubes can be configured, as depicted in Figure 2 (*right* column). All tubes can be actuated uniformly as one unit, which is the simplest configuration. Users may choose to form pneumatic groups of different numbers of actuators,

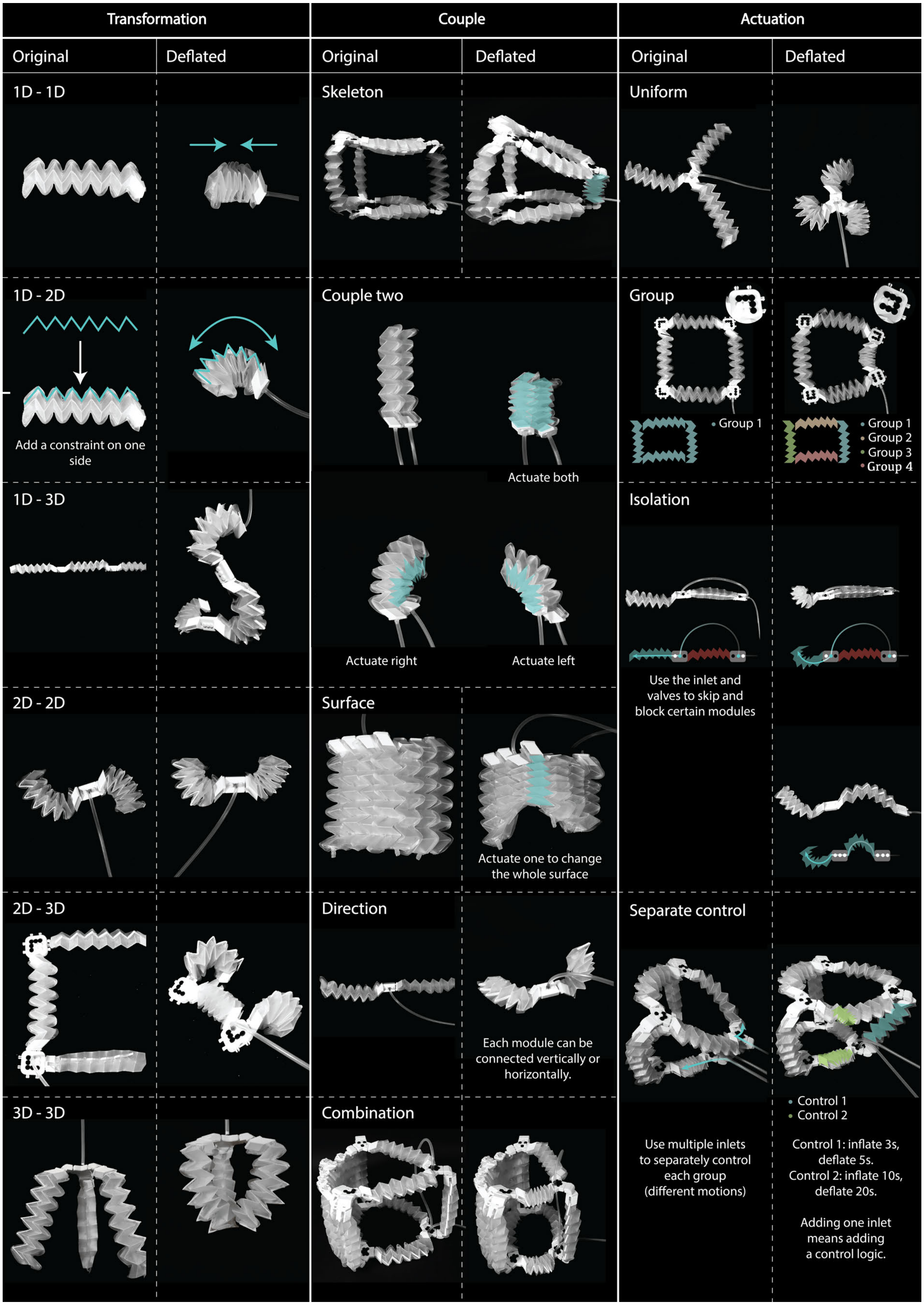

Figure 2: We outline the design space that our MiuraKit covers and depict primitives and their transformation.

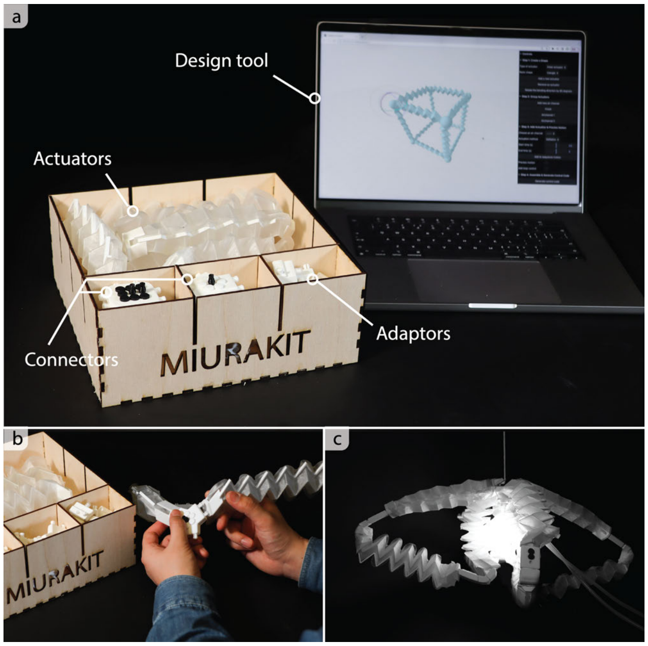

Figure 3: Our MiuraKit consists of (a) soft actuators, connectors, and adapters for spatial and pneumatic configuration, and an interactive design tool. It is designed to (b) support hands-on exploration of (c) shape-changing applications (here, a lamp).

e.g., grouping 3 tubes to be actuated as one entity and actuating the 4th tube individually. For complex shape-changing applications, users may choose to control coupled tubes separately.

Why Miura-ori over other patterns. Since soft actuators are an active research topic in engineering disciplines, we investigated several cylindrical origami tube designs before choosing the Miura-ori pattern for our actuators. We evaluated the Yoshimura tube, which has similar properties to the Miura tube in that it can be compressed linearly and has omnidirectional bending abilities. However, its geometry of it is not easy to be combined for shape morphing [11, 40]. The Kresling tube exhibits compressing-twisting deformation which makes it not easy to be connected [59]. The bistable origami tube can maintain its deployed shape without the need for continuous actuation, but it can not be used for flexible bending motion [27]. Therefore, we choose the Miura-ori pattern as it is simple and allows for the most flexibility to be reconfigured to use [8].

3.2 Connector Design

To enable hands-on building with pneumatically driven origami actuators, we developed a novel connector that allows users to configure both the spatial arrangement of Miura tubes and their pneumatic grouping for dynamic control.

3.2.1 Mechanical Connection. Our connector enables users to couple Miura tubes spatially. As shown in Figure 4a, we use snap-fits for the assembly and disassembly of the parts, such that users can reuse them for different designs. The kit includes 2 versions of the connector, i.e. rectangular one to connect up to 4 Miura tubes and a triangular one to connect max. 3 tubes, as shown in Figure 4b. By default, the connectors couple the tube in plane. To enable users to create 3D spatial arrangements, we include 5 adapters in our kit, as shown in Figure 4c. They use the same snap-fit interface and can be simply inserted between the connector and the tube.

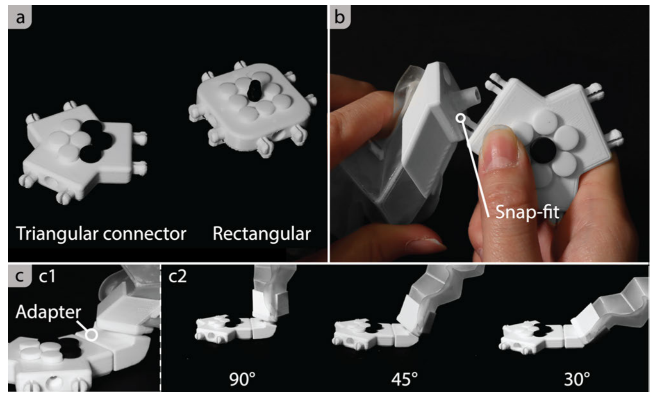

Figure 4: We offer (a) connectors for rectangular or triangular arrangements of tubes. The connectors feature (b) snap-fits for hands-on assembly and disassembly. To support 3D connections, we offer (c) several adapters in 30°, 45°, 60°, 75°, and 90°.

3.2.2 Pneumatic Configuration. Beyond the mechanical connection, users need to be able to configure how the Miura-ori actuators are controlled. Since we use pneumatic actuation, users need to be able to configure the air groups, i.e., which tubes should move together and which should move at a different time. Again, we want to enable users to do this configuration hands-on. We designed our connector with simplicity of use in mind while offering many configuration options. As we have shown in Figure 6a, our connector has air channels on the inside, which can be configured with simple silicone plugs. The shorter white plugs let air pass through the channel, while the longer black plugs block that channel. The colors are intended to signify the air channel configuration to users intuitively, as shown in Figure 6b. Additionally, each slot can be used as an inlet for the air source to form new independent air groups, as shown in Figure 6c. These few parts (plugs, inlets) paired with our intentionally simple connector design allow users to achieve all permutations of possible air groups.

3.3 Control Board

When users configure multiple air groups with our connector, they will want to control the timing of actuation with valves. The electromagnetic valves are controlled by an Arduino microcontroller which switches the negative pressure from the vacuum pump on or off. While we used standard off-the-shelf components in our research prototype, the recent rise in pneumatic control kits for novice users, such as FlowIO [47] or Pneuduino [37] is a promising extension to this construction kit. In this prototype, we used two-way two-position solenoid valves (HOFUJING 2V02508) and a

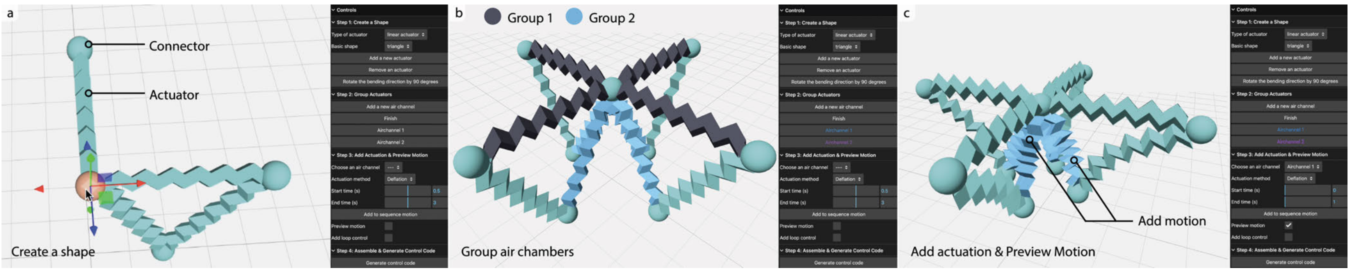

Figure 5: Walkthrough of step1, 2, and 3 of the interactive design tool.

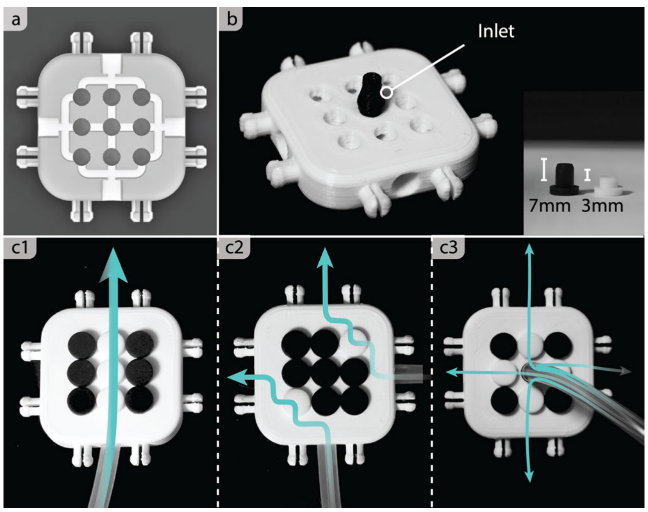

Figure 6: Our MiuraKit connectors have (a) integrated air channels, which (b) can be configured manually by inserting simple silicone plugs to let air through (white plugs, short) or block the airflow (black plugs, long). (c) We show different configurations, including one featuring an additional inlet.

stationary 8 CFM vacuum pump (Robinair 15800 VacuMaster Economy) for actuation and control. Note that a vacuum chamber can be used for actuation to avoid the noise of the pump.

4 INTERACTIVE DESIGN TOOL

We provide a web-based design tool to assist novice users in creating desired shape-changing or robotic structures and previewing their motion with our origami actuators. The user workflow consists of the following steps.

4.1 Step 1: Creating a Structure

Users can create an arbitrary shape-changing object by connecting linear or bending origami actuators with different angles in the user interface (Figure 5a). By default, the viewport shows a simple triangle with three linear actuators to help users get familiar with the software. To add one new actuator, users start by clicking a connector and selecting an operating axis, and then they can rotate the newly generated actuator around the operating axis to a specific angle with a 15 degrees rotation snap. Users can also remove an existing actuator by clicking it or changing the bending direction of one bending actuator. During the editing process, a connector is automatically added to the end of a new actuator. All connectors are shown as spheres in this step. In the future, an inverse design pipeline can be implemented to help users design complex shapes with expected dynamic motion, e.g., locomotion, rolling, or jumping.

4.2 Step 2: Grouping Origami Actuators

Having different origami actuators work independently enables versatile shape-changing behaviors. Thus, our user interface supports users to configure multiple air channels by selecting different actuators into a group that shares the same air chamber. We show the interface in Figure 5b. Actuators across different groups will be displayed in different colors. Actuators that do not belong to any group will not be simulated in the next step.

4.3 Step 3: Previewing Motion

Next, the system allows users to specify the deflation or inflation status for each air channel in a sequential time. They can specify the start time and the end time of the actuation. Then, users can preview the real-time motion of the actuators to test if the shape-changing object works as expected (Figure 5c). If not, they can go back to the above steps to re-edit the shape or re-arrange the air group of the object.

4.4 Step 4: Physical Assembly & Generating Control Code

Once satisfied, users can assemble the designed objects with the components in our MiuraKit. After that, they can let the system generate a control code for the Arduino board to control the switching state of the electromagnetic valves. The control code is automatically saved as a *.ino* file which users can directly upload.

4.5 Software Implementation

Our interactive design tool uses *Cannon-es* [3], a lightweight 3D physics engine, to simulate the motion of the origami actuators, e.g., deflation, inflation, and bending. We also use *Three.js* [51] to render the scene and geometry of the Miura-ori tube, and uses *lil.gui* [22] for the user interface interactions. All the code is written in JavaScript and tested on Google Chrome. We open-source our code[1] for replicability.

[1]https://github.com/zhitongcui/Origami-Actuators

The deflation of the actuator is approximated by simulating the rigid folding process of the miura-ori tube, thus, the inflation is the deployable process of the tube. To simulate the rigid folding behavior with cannon-es, we treat each quadrilateral of the Miura-ori tube as the triangle mesh shape [4] in cannon-es, and then we define the mountains and valleys of the origami creases as hinge constraints with opposing orientations. After applying a force to each hinge, the origami will fold at a specified speed, which simulates deflation. Meanwhile, to avoid the collision of each quadrilateral, we set the velocity of all the physical bodies to zero after detecting a distance threshold, which is the thickness of the actuator after deflation. To simulate the bending behavior of the actuator after adding a mechanical constraint, we apply different stiffness values and opposite velocity directions to the hinge constraints on the different sides of the Miura-ori tube geometry. All the parameters are fine-tuned to approximate the actuation performance of the physical actuators.

Users can add a new actuator by clicking an existing connector. When adding a new actuator, connectors on the two ends of it are automatically attached with a lock constraint, which removes all degrees of freedom between them. Thus, the connectors always move with the actuator. Whenever the system detects that there is an existing connector in the end position of a newly added actuator, the system will lock them together for interconnect movement.

In the software, the airflow of each actuator is programmed based on the users' group arrangement of actuators. The connector that connects actuators within one group is treated as the only air inlet for the previewing motion process. We then generate the Arduino control code based on users' settings of grouping air channels and sequence of motion. The parameters and pre-defined control code are initialized as a file-like Blob object[2], and then saved with the *.ino* file format which can be directly uploaded to the Arduino board.

5 APPLICATIONS

To highlight the capability of our construction kit, we demonstrate a series of design examples.

5.1 Shielding Chair

We implemented a demonstration of an organic chair that can react to its environment and change its shape to communicate to others. Figure 7 shows how the chair resembles a porcupine to communicate that the user is in focus mode and does not want to be disturbed. As the user switches to simpler tasks, the spikes, that are implemented with our Miura tubes, soften and appear more inviting. This is an artistic take on a focus communication tool, which our MiuraKit allows to prototype quickly.

Additionally, we implemented shape changing arm rests, as shown in Figure 8. The arm rests consist of Miura tubes coupled as surfaces, which are upright (non-actuated) when users work, but can curl (actuated) to hug the user's body to comfort them. We implemented the physical side of this application, which could be combined with algorithms from the affective computing field for emotion detection.

[2]https://developer.mozilla.org/en-US/docs/Web/API/Blob

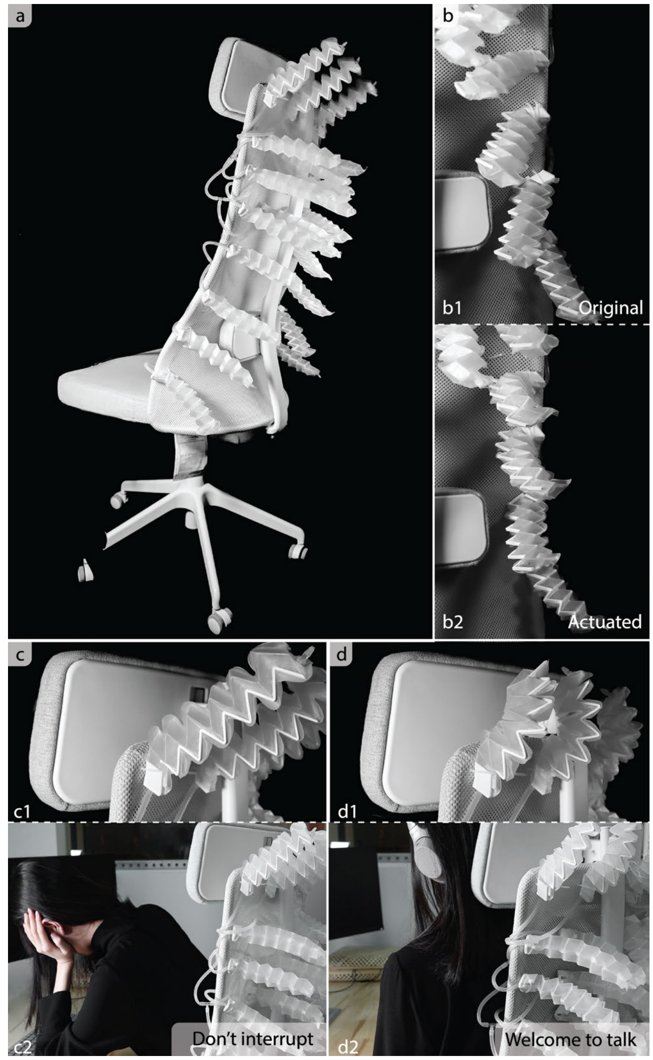

Figure 7: Our example application of a shape-changing chair to protect users' focus time for deep work.

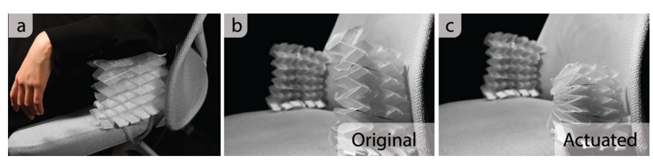

Figure 8: (a) Our example of an arm rest. It (b) is straight for regular work, but can (c) curl to hug the user upon detecting emotional distress.

5.2 Shape Changing Lamp

Figure 9 shows a shape-changing lamp application. This application showcases how Miura tubes can be connected into a 3D shape and be integrated with external objects, here a light bulb. The lamp shade can change its shape to adapt how the light is shed through its structure.

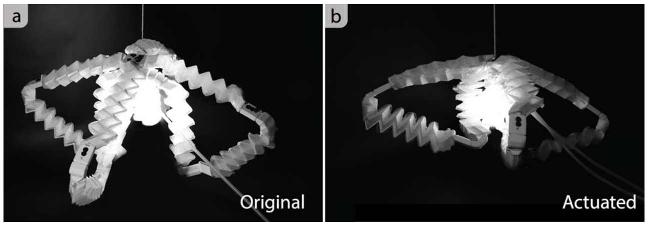

Figure 9: A simple shape-changing lamp example made with MiuraKit.

5.3 Interactive Curtain

We also showcase an interactive curtain application, which is constructed with MiuraKit. We sew simple linearly coupled Miura tubes onto the backside of a curtain (see Figure 10a-b). The tubes add interactivity to the curtain. In this scenario depicted in Figure 10c-e, a user left a small gift for their friend. The gift is initially hidden behind the curtain, but is being revealed when their friend enters the room, which triggers the shape change to reveal the gift. Additionally, we demonstrate how the curtain implements telepresence-like interactions in Figure 10f. Here, a user wants to stay connected with their sibling, who lives on a different continent now. They connect their curtain to the keyboard of their sibling, which triggers the curtain to 'dance' when their sibling plays the keyboard—an activity they used to do together.

5.4 Envisioned Application Space

We illustrate the larger application space that we envision in Figure 11, which goes beyond our exemplary research prototypes shown here in this paper. We see potential in new designs of shape-changing interfaces in domains such as large-scale interactive walls, embedded within furniture for object manipulation, robotic applications, or deployable shelters. Once non-experts have tools, such as MiuraKit, for shape-changing interfaces in hand, the potential for a larger push in dynamic interfaces and objects is fathomable. We believe that the creativity of the mass can be a catalyst for new technology.

6 USER STUDY

We conducted a user study to validate the construction process of dynamic shape-changing interfaces with our construction kit. The aim of this study was to observe how users would engage with our construction kit to realize their independent ideas.

Participants. We recruited 8 participants, mainly from our institution or visitors. They were compensated with $15/hour for their participation. All had no prior experience with designing or constructing shape-changing interfaces, soft robotics, or with fabrication processes. Our participants (3 female) were between the ages of 24 and 32 years (M = 26.14, SD = 2.53).

Procedure. After greeting the participants, obtaining their consent, and having them fill out a background questionnaire, we first introduced them to the construction kit. We walked them through the components of the kit, showing (1) how the Miura-ori Actuators compress or bend, (2) how the air paths can be configured

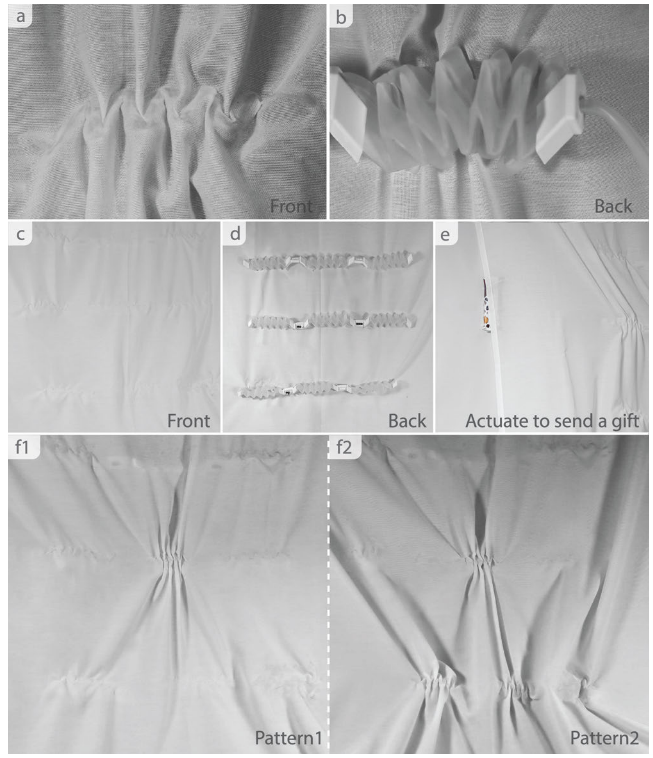

Figure 10: We show an interactive curtain application. (a-d) The MiuraKit parts are attached to the back of the curtain. In our scenario, the curtain can (e) reveal hidden objects or (f) move in a rhythmic pattern.

on the connector, (3) how the adapters snap together to enable different spatial arrangements, and (4) how to use the software to edit a shape, simulate the motion, and export the control code for actuation. We spent about 10 min on this walkthrough.

After this introductory walkthrough, we left the participants with the pictorial of our primitive library shown in Figure 2 and asked them to design and build a shape changing interface of their choice. Participants were asked to perform this task on their own and to think out loud. The study conductors took notes during the session and reminded participants to verbalize their thoughts if necessary. If participants asked for help, the study conductors encouraged them to find a solution on their own and referred them back to the depicted and demonstrated shape-changing primitives.

After about 40 min of creating their own shape-changing objects (see Figure 12), the study conductors performed about 10 min of semi-structured interviews with the participants to further understand their experience with our MiuraKit. Participants were asked to comment on (1) the utility of the kit and if it supported them in making their envisioned objects, (2) their experience using the kit, and (3) on the main benefits and challenges of this kit. At the end, we also gave our participants the opportunity to add any other comments or suggestions. We recorded the data by taking notes during the study sessions and through video recordings.

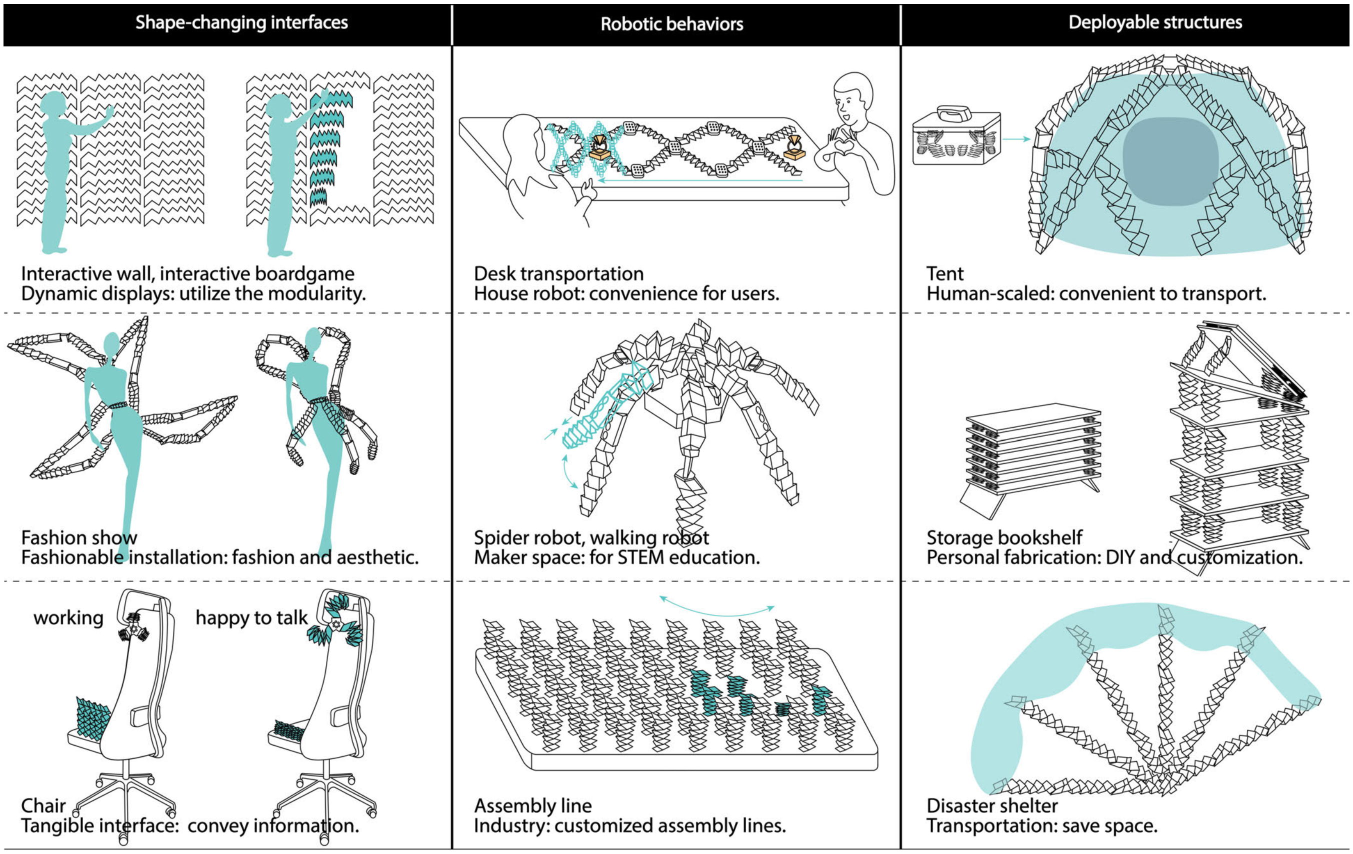

Figure 11: Beyond our implemented application examples, we outline ideas for a larger application space, spanning large-scale, fashion, robotics, or deployable structures.

Figure 12: During our user study, participants had access to all MiuraKit components.

6.1 Results

As a result of this study, participants made a range of objects, including a dynamic interlocking chain (P1), a three-legged walking robot (P2), a shape-changing clothing hanger (P3), a directionally actuated lamp (P4), a simple swimming robot (P5), a hugging dog puppet (P6), a dynamic flower (P7), and a model of adjustable train tracks (P8). We show 4 of their creations in Figure 13. We discuss the participants' comments from the study session in the following.

Usability. Generally, all participants expressed that the construction kit is easy to understand. In particular, they mentioned how the actuators work, and that the pneumatic and mechanical configuration with our connectors was clear and understandable. P5 said "*I think it took me less than 5 min to learn. I could understand how this kit is moving, how the motion was built, and what things I can do with it.*" Similarly, P2 explained that "*The affordance is very clear, I know in which direction the bending tube will bend and how it will contract. I can also clearly understand how the pneumatic connectors work and how the connectors can help me group the air chambers. The mechanical connector is easy to use.*" P7 and P8 explicitly stated that the black and white colors of the silicone plugs facilitates their understanding of the air groups, with P8 saying "*I can just imagine there is a path.*"

The participants also commented on the control of their shape-changing object, with P8 wishing for full automatic control of the air supply, but P2, on the contrary, mentioning that they preferred the hands-on pneumatic configuration because it was straightforward. We did not have the participants use our design tool for the study, which would allow them to independently control their objects. Instead, the study conductor helped them with actuating their design, which left some participants wishing for more independence. Our design tool will come in handy.

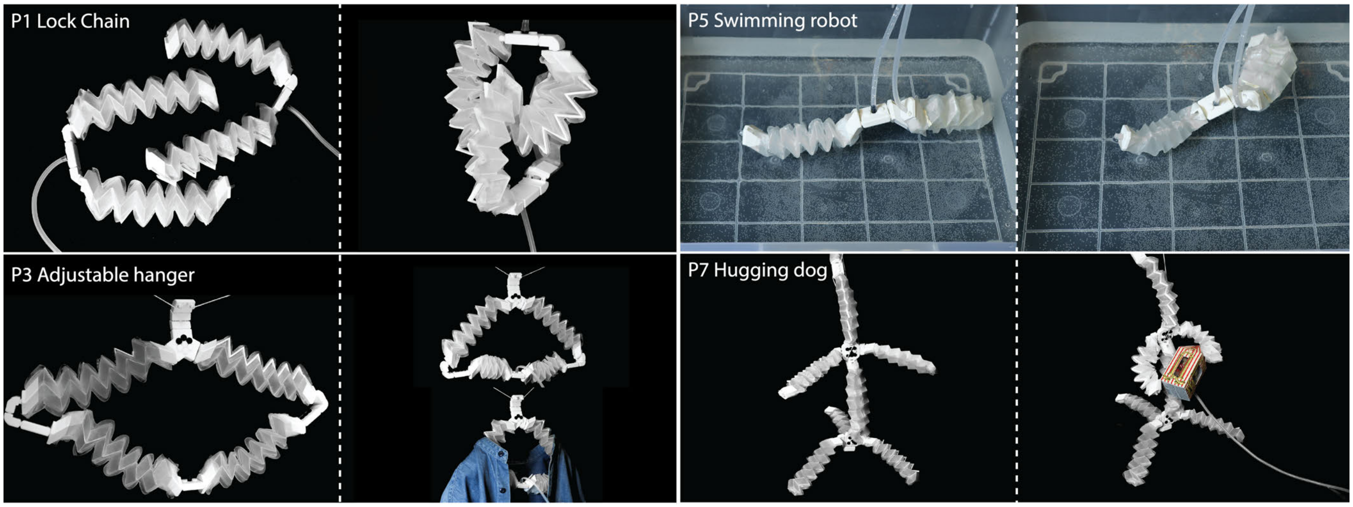

Figure 13: An overview of the shape-changing designs that our study participants built.

Our participants mentioned that they noticed air leakage, which the study conductors again helped with. This was the major critique of participants, which further confirms the need for non-user fabricated parts. While our research prototypes were still made in the lab, this confirms that industrially manufactured parts are necessary and that our easy-to-understand components are a viable path we will pursue further.

Utility & Creativity. Our participants expressed that the kit supported their creativity with the multiple degrees of freedom and the flexible configuration of connectors. For example, P1 originally intended to build crab claws, but pivoted to an interlocking chain after experiencing deformation of the tubes, which sparked a new idea. In total, six of our participants considered the hands-on exploration of creating desired shape-changing objects as interesting. P2 noted "*It's very cool, I like it. It's like creating artificial creatures.*"

P4 said that they like how MiuraKit makes the physical design process like tinkering, which can be thought of as "thinking with your hands". P2 and P7 compared our construction kit to Lego, but for movement. P6 said that the kit "*is helping me to imagine how it will move rather than how it looks. I mean I was thinking about both of them [shape and movement], but a lot of times when you make something you're more focused on how it looks.*" P6 further compared the static thinking about the shape to Lego, which is in line with our design goals of providing a dynamic construction kit. They also mentioned that MiuraKit might be beneficial in education, e.g., to educate children about mechanisms.

Future extensions. Participants had very valuable feedback for future extensions to the kit. Three participants mentioned that they could see use in allowing connectors to be connected to each other, such that they can connect more actuators around them for more versatile shapes. P7 also suggested producing the adapters in different colors to color-code their angle and making them easier to find. P3 and P6 mentioned that they can see actuators of different lengths or different diameters being useful for high-resolution or large-scale shapes. On the same line, P1, P7, and P8 also envisioned that they can build some human-scale objects with our construction kit.

Overall, the feedback from the participants confirms that such kits must be professionally produced for robustness for real-world use and that our kit is a promising design. They thought that our construction kit is very easy to understand and that the hands-on building does support their creativity around movement and shape-changing objects. Participants then proposed expanding the kit by different sizes of actuators such that they could use it for an even wider range of applications across scales.

7 LAMINATING ORIGAMI ACTUATORS

Our construction is designed explicitly such that users do not have to fabricate anything, but rather obtain the kit with all necessary components. However, for replicability of our work, we describe our fabrication process of the tubes. Our fabrication method builds on fast fabrication techniques that are common in industry. We use laser cutting and lamination via heat bonding.

The first step in our fabrication method is to laser cut the outside and engrave the creases of the Miura tube pattern, as shown in Figure 14 *(top)*. We use 0.6 mm PETG material that we heat bond to 0.2 mm transparent TPU film using a heat press (Figure 14 *(center)*). This results in one side of the Miura tube fold pattern. We then seal the outside of the two halves of the Miura tubes together by placing them in a mold that raises only the outside of the Miura tubes to receive heat and melt the TPU locally (Figure 14 *(bottom)*). In this step, we place a strip of TPU on the inside, which we pull to keep the Miura tube in a pre-folded state, preventing it from going flat under suction. This strip is also heat bonded at its top and bottom to the TPU of the tube. We then place the barb connectors into the top and bottom of the Miura tubes by piercing small holes and screwing them in using a small gasket. Lastly, we glue the rigid connectors that will receive the snap-fit connections onto the tubes.

After this fabrication process, our Miura tube actuator has a length of 16 cm and a width of 3.5 cm. Our tubes contracts to their compact state within about 0.2 s, which we actuate with a 8 CFM[3] pump (Robinair 15800 VacuMaster Economy Vacuum Pump). The Miura tube provides a force of about 12 N when contracting. When actuating multiple Miura tubes in parallel, the speed and force will decrease proportionally to the total volume.

8 CONCLUSION

We presented MiuraKit, a construction kit for immediate hands-on exploration of shape-changing interfaces. Our kit provides generic soft actuators that incorporate the Miura-ori pattern. We developed a novel connector for users to couple the actuators into their desired applications by snapping them together. Additionally, the connector allows users to configure the air paths going through their structure hands-on in a compact design. Users can couple the actuators as a skeleton, as surfaces due to the tileable nature of the Miura pattern, or a combination thereof. Our user study shows that novice users understood our construction kit very quickly and felt supported in making shape-changing and robotic interfaces.

In the future, we plan to further investigate MiuraKit's utility through long-term studies. We plan to give it out to design firms and schools to evaluate it over several weeks. To do that, we also plan to investigate smaller-scale air supply, such as FlowIO [47], or integrate micro air pumps within the Miura tubes. Additionally, we plan to establish automated manufacturing options to prepare for a larger-scale study.

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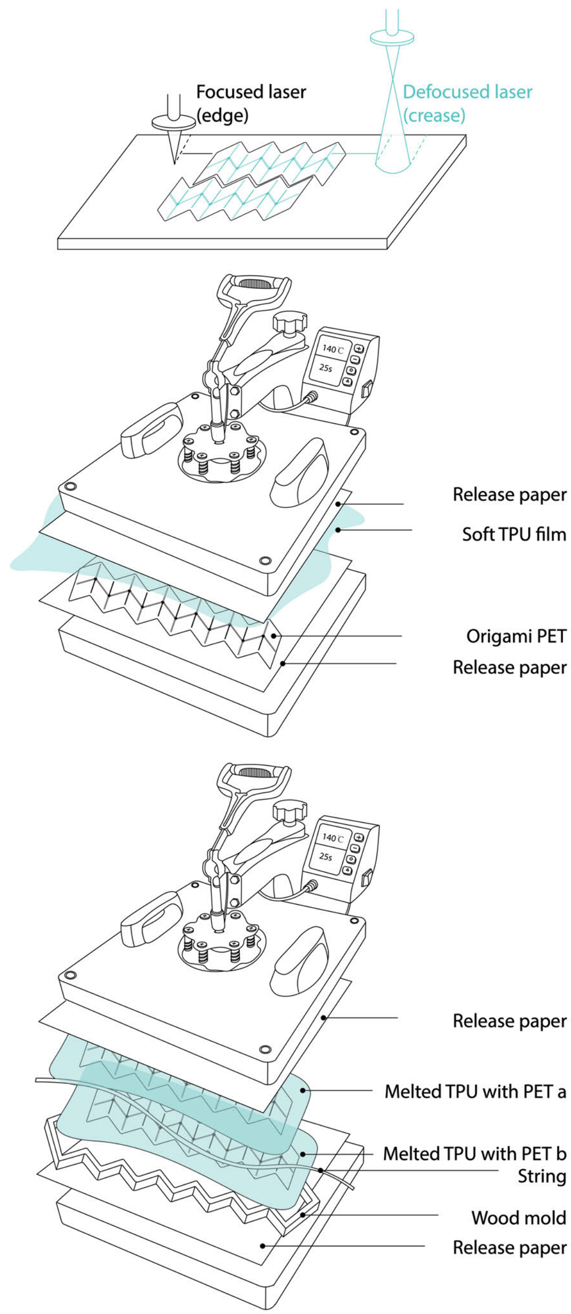

Figure 14: The lamination process we used for our research prototypes of the Miura-ori tubes. We aim for professional mass fabrication in the future.

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