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Mimosa: Modular Self-folding Hinges Kit for Creating Shape-changing Objects

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ABSTRACT

We developed a shape-changing constructive kit, named Mimosa[1]. A key component of the toolkit is the modular hinges, each of which is equipped with two antagonistic shape memory alloy (SMA) wires. One wire deforms the hinge to approach its predetermined angle at high temperature, and another wire drives the hinge back when it cools down. Hinge leaves are available in different materials including acrylic, cardboard and textile, which increases the versatility of the toolkit. Every hinge weighs 2.1-5.4 g, and generates up to 5.7 N actuation force. A Bluetooth control module was developed, enabling remote control of the shape-changing objects. Mimosa aims to inspire designers to explore and create interactive shape-morphing objects with SMAs. A few examples are given such as a gripper, a rolling robot, a butterfly, an airplane and a self-closing pocket. A workshop study with 6 participants showed that Mimosa indeed motivated and inspired the participants to create new ideas.

CCS CONCEPTS

• **Human-centered computing → Interactive systems and tools**.

KEYWORDS

Shape-Changing Interfaces, Tangible User Interfaces, Toolkit, Shape Memory Alloy, Smart Hinge, Crafting

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1 INTRODUCTION

"*High-tech*" usually refers to computation, and the rest of the material world is often regarded as "*low-tech*" (or craft) [9]. In 1999, Eisenberg defined "*middle tech*" as a "terrain in which programs and materials, complexity and concreteness, blend into new media" [9]. In the *middle tech* terrain, computation and crafting are deeply woven together without firm lines. On the craft side, computation enhances the expressive capabilities of existing materials. On the computation side, new software and programs are developed to support crafting activities [3]. The boundary between computation and craft gradually disappears. This can for example be observed in the smart textile domain, where many electronic toolkits and software are developed to blend with traditional textile manufacturing techniques [12, 20, 59, 64]. Vallgårda and Redström proposed that computational technology could be seen as a material like any other materials used to design things [60]. In Seymour Papert's project, students could use any materials to build devices for time measurement. The computation can be "*messed around with*", just like pendulums, paints, clay [11]. Blending computation with traditional craft can be seen as a promising approach to develop new devices, increase technological literacy and broaden technology culture [42]. Leah and Hannah also demonstrated such benefits of combination of craft and computation by integrating carving, sewing and painting into constructing electronics [4]. In recent year, pandemic lockdowns prompt reflections on crafting tangible interfaces in home [19].

Shape-changing interfaces are emerging as a new generation of devices which can change their shapes [21]. A common form of shape-changing interfaces is represented by construction kits, which consist of interactive units that can be assembled and connected [7, 58]. Construction toolkits can encourage users to explore creative concepts in an easy and efficient way [67]. Many researchers have recently explored application potentials of shape-changing toolkits. Most of the existing toolkits are developed for particular applications, such as kinematic system education [45], adaptive furniture [50], and children entertainment [25, 65], and some toolkits have already incorporated the traditional crafting [24, 43]. However, the potential of shape-changing toolkit in the *middle tech* terrain has not been fully realized. Combining traditional craftsmanship with tangible user interfaces design is beneficial for the development of new devices, as crafting provides users with greater creative freedom, enabling them to customize the devices in a personalized manner [18, 40]. It is worthy to encourage users to immerse themselves in the *middle tech* exploration, by integrating crafting activities with "*high-tech*".

This paper presents Mimosa, a shape-changing constructive kit based on shape memory alloy (SMA) technology. By incorporating everyday materials (e.g. cardboard and textile), Mimosa encourages designers to participate in craftsman and aims to inspire them to create shape-changing objects for a variety of application scenarios. SMA can generate a relatively high actuation force, which may

[1]Mimosa is a genus of plants that can "change their shapes" in response to external stimuli.

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enhance the toolkit's versatility. Additionally, SMA is lightweight with a small form factor, and thus has little effect on the overall aesthetics of the shape-changing objects.

Several ways of characterizing how physical tools support creative practices has been introduced in previous HCI research [34, 55, 57, 69]. Here 4 metrics are derived to evaluate Mimosa, which are *usability*, *transparency*, *quality* and *agency*. *Usability* refers to whether the toolkit is usable or not. *Transparency* addresses the awareness of the toolkit during creative practice [34]. *Quality* describes users' satisfaction on the final objects constructed by the toolkit, and users' affective feelings after using the toolkit. *Agency* refers to whether users are capable to make customized designs. We aim to ensure that Mimosa closely adheres to these metrics, thereby maximizing the toolkit's support for users' creativity.

With Mimosa, we make the following contributions:

(1) We provide a toolkit for constructing shape-changing objects, by incorporating the crafting (e.g. sewing, papercraft) process. The toolkit's compatibility with everyday materials allows for craftsmanship and boundless creative potential.

(2) By making Mimosa simple and accessible, we offer an efficient way of using SMAs for constructing shape-changing objects. Users without any prior experience of similar toolkits can construct their shape-changing objects in one hour.

(3) With a workshop study, we demonstrate the toolkit can inspire users to design, and provide a good user experience. Lessons we learn can inform future toolkit improvement.

2 RELATED WORK

2.1 Motor-based Shape-changing Toolkits

Motors can be controlled easily and precisely (e.g. rotation angle, speed). They can provide lots of possibilities to achieve complex shape-changing behaviors. For examples, serpentine robotics *LineFORM* is a curve interface for display, interaction and constraint. It is comprised of a series chain of 1DOF servo motors with integrated sensors for direct manipulation [38]. Users can set their shapes in software. *Topobo* is a constructive assembly system actuated by motors and electronics. It can be quickly assembled to produce dynamic biomorphic forms like animals' skeletons [45]. *Topobo* is targeted at children, to help them understand certain physical principles affecting kinematic systems. Leigh et al. presented *Morphology Extension Kit*, which allows users to build and customize wearable robotics [28]. In addition, *Roombots* [50] for adaptive furniture and self-assembling cubic robot *M-Blocks* [47] are also modular shape-changing objects actuated by motors.

Existing motor-based toolkits have limited versatility, as some of them are developed for specific purposes (e.g. *Topobo*, *Morphology*, *Roombots*), and some (e.g. curve interface *LineFORM*, cubic interface *M-Blocks*) cannot be used for constructing complicated shapes which can limit their application scenarios.

Using motors for developing shape-changing toolkits can produce some unavoidable problems. First, to achieve complex shape-changing behaviours, a certain number of motors is necessary which makes shape-changing objects bulky and heavy. Second, joint spaces need to be foreseen for placing the motors, that might affect the aesthetics of constructive shape-changing objects. Third, noise is generated when the motor is running.

2.2 Pneumatic Shape-Changing Technologies

A pneumatically actuated approach (e.g. with air-pumps) can be used to control movements or shape changes of devices. Some technologies and methods have been put forward to create shape-morphing objects. Such technologies encourage users to design air bubbles themselves, which can be seen as a crafting activity. It enables users to create customized shape-changing objects, but the duration time is long. For instance, *PneUI* developed by Yao et al. is used to build shape-changing interfaces through pneumatically actuated soft composite materials [66]. For each *PneUI* application, users need to design and construct different composite interfaces which include diverse air bubbles or channels and structural material layers (e.g. paper, fabric, wood). It involves the silicone casting process with 3D printed molds, which could be time-consuming.

MorpheesPlug, which covers seven shape-change features (such as length and curvature change) with six types of widgets, can be used for designing different items (e.g. an anti-rain phone case and posture-correcting cushion) [21]. *TEX(alive)* is another toolkit using 3D printing technology, which serves to help familiarize designers with the complexity and expressivity of temporal forms in shape-changing textile interfaces [33]. *Therms-Up!* is a DIY method of creating inflatable soft actuators with wasted thermoplastic bags and a 3D printer [5].

It is easier for users to construct shape-changing objects by providing ready-to-use modular components. *InflatiBits* is a modular construction kit consisted of soft inflatable air-chambers, air-connectors, and etc. By combining with standard LEGO parts, the constructed customized soft robotics can achieve fantastic appearances [25]. Similarly, *Legoons* is developed for constructing characters and artifacts [65]. It consists of several types of inflatable widgets and decoration bricks for children to make inflatable animals, a long chain, and etc. Lee et al. developed a system of Lego-compatible pneumatic bricks for customizing soft robotics (e.g. children toy, gripper) [27].

In most cases, an air pump is necessary for the activation of pneumatic shape-changing objects, which could make the devices bulky. Even though there have been some pump-free designs available [1, 52], there are still various restrictions when it comes to applications. For example, Webb et al. presented *Auto-Inflatables*, which can be activated by the chemical reaction in chambers, but it is a one-time activation mode [62]. Lu et al. developed fluid-driven *milliMorph* [32]. When filling with low boiling point liquid, it can be triggered by the environment temperature without any pump and rigid components. However, its actuation force is relatively low, which can limit its application scenarios. Similarly, many pneumatic toolkits, like *InflatiBits*, *Legoons* and *Soft LEGO*, only address at the field of entertainment for children owing to their low actuation force [27].

2.3 Pin-based Shape-Changing Displays

Pin-based shape-changing interfaces refer to interfaces that use an array of vertically moving pins to render different shapes and forms [48]. Many relevant devices have been proposed in the HCI community [10, 16, 29]. For examples, John et al. developed modular *ShapeClip*, which can help users transform any computer screen into a z-actuating shape-changing display without requirement of electronics and programming knowledge [15]. Such pin-based displays have limitations on the types of shapes that can be achieved, as the pins can only move up and down without capacity to render any overhang or overpass structures. Philipp et al. addressed it with magnetic building blocks on the pins [48]. Pin-based shape-changing displays generally are used for enriching output modalities of existing displays instead of creating shape-changing objects, as the pins have to be installed in a "platform" to help them move vertically.

2.4 SMA-based Shape-Changing Toolkits

SMAs have been used as actuators in many research works [31, 36, 46], and are also applied in some shape-changing toolkits. For examples, Tahouni et al. presented *NURBSforms*, which is a modular shape-changing tool for prototyping curved surfaces [54]. Each module represents an edge of variable curvature, and it enables designers to construct and adjust surface's curvature when joined together with other modules. Similarly, *Surflex* is a programmable tangible interface which contains embedded SMA coils [6]. *Patch-O* is a deformable interface fabricated with versatile yarn materials and SMAs [26]. It can enhance functionally of garments and aesthetically suited in the form of a woven patch. Application cases include a volumizing hair lifter, a shrinking patch for lifting sleeves and etc. [26]. SMA shape-changing displays can also function as notification interfaces, such as *MorePhone* [13]. In addition, there have been some shape-changing interfaces integrating crafting with SMA, such as the animated paper [24, 43], and *Seamless Seams* which embeds SMA wires on fabrics [37], but each of them only address at one application field (i.e. education, toy and interactive artefact).

3 MIMOSA KIT COMPONENTS

In this section, toolkit Mimosa will be introduced. Mimosa consists of 5 main components as depicted in Fig. 1. Each element has been described further:

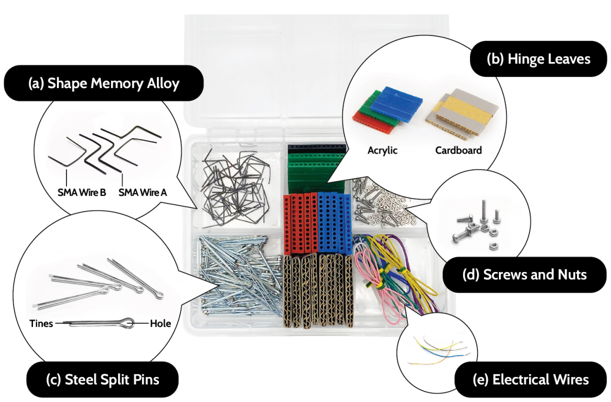

Figure 1: Mimosa Components. (a) Shape memory alloy; (b) Hinge leaves; (c) Steel split pins; (d) Screws and nuts; (e) Electrical wires.

3.1 Shape memory alloys (SMAs)

Shape memory alloys are a type of smart materials which can "remember" their original shapes after training. The training process can be seen in the appendix A1. The ability of SMA to return to a predetermined shape when heating above the transformation temperature (Austenite finish temperature, A_f) is referred to as *shape memory effect (SME)* [2]. For example, as can be seen in Fig. 2 (a), the *SMA wire A* (with a predetermined angle 180° and A_f= 47 °C) can be deformed to 0° (or any other angle) in a low temperature environment, but when it is heated above 47 °C, it will go back to its original angle, which is 180°. In addition, the ability of a SMA to recover large strain with associated stress-strain hysteresis due to mechanical loading-unloading under isothermal conditions is referred to the *superelastic effect (SE)* [61]. Such effect can be observed when the temperature is above A_f. As depicted in Fig. 2 (b), if the *SMA wire B* (with the predetermined angle 0° and A_f=-4 °C) is deformed to any angle in room temperature, it would recover to 0° when the force is released.

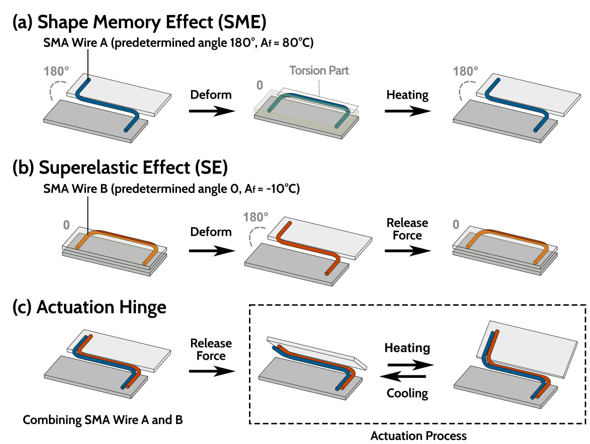

Figure 2: (a) *Shape Memory Effect (SME).* When one SMA wire is combined with two rigid plates, the wire angle refers to the angle between the plates. If it is 180°, the two plates are placed separately and in parallel. (b) *Superelastic Effect (SE).* (c) Actuation Hinge. During heating and cooling, the hinge actuator can repeatedly change its angle.

When the *SMA wire A* and *B* are combined (see Fig. 2 (c)) as an actuator hinge in low temperature environment, the *SMA wire B* tends to recover to 0 ° owing to the *superelastic effect*, so it generates force on the hinge to change its angle. Usually the angle of the actuator hinge cannot reach the original angle of the *SMA wire B* (0° in this case), because the *SMA wire A* also generates force on the *wire B* to prevent the hinge to go back to 0°. As a result, the actuator hinge stops at a certain angle close to the original angle of the *SMA wire B* (see red dashed line in Fig. 3). The situation becomes different when the actuator hinge is heated above the A_f of the *SMA wire A*. Owing to the *shape memory effect*, the *SMA wire A* becomes stiffer and tends to drive the actuator hinge to go back to its original angle (180°) (red solid line in Fig. 3). Nevertheless, the actuator cannot achieve 180° due to the opposite force of the *SMA wire B*.

During heating and cooling, angle the actuator hinge can repeatedly change between two pre-set SMA angles. Such phenomenon is similar to the *two way shape memory effect (TWSME)* [53], as it can remember two different shapes: one at the low temperatures, and another at the high temperature. The only difference is that in our case we use two different types of SMA wires to create that effect (instead of one single SMA wire). Two SMA wires are preferred over a two-way SMA wire since this improve reliability and avoid a complicated process. A similar configuration of the SMA wires has been presented by Koh, et al. [51], and additional research can be found in [22, 49].

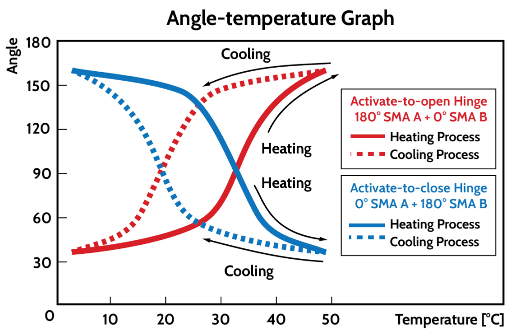

Figure 3: Angle-temperature graph of two types of hinge. Red color lines are the actuation process of *activate-to-open* hinge, while blue lines are *activate-to-close* hinge's. Full and dashed lines represent the heating and cooling process respectively.

There are many parameters which can affect the original and actuation angle of the actuator hinge, such as the pre-set SMA angles, diameters of the SMA wires, lengths of the SMAs in the torsion part (see Fig. 2(a)). Here we only consider the influence of the preset angles of the SMA wire. We finally define two types of actuator hinges ("*activate-to-open*" and "*activate-to-close*") by combining SMA wires with different initial SMA training angles. We used the 1.00 mm diameter SMA wire (A_f= 47 °C) from Nanografi Nano Technology as *SMA wire A*, and 0.75 mm superelastic wire (A_f= -4 °C) from Kellogg's Research Lab as *SMA wire B*. For the *activate-to-open* hinge, the predetermined angle of *SMA wire A* is 180°, while for *SMA wire B* it is 0°. The *activate-to-close* hinge consists of a *SMA wire A* with the preset angle of 0°, and a *SMA wire B* with the preset angle of 180°. Fig. 3 roughly shows how the angles of two types of hinge change with temperature.

3.2 Hinge leaves

Hinge leaves are developed in different materials, including acrylic, cardboard and textile. Comparing with commonly used 3D printed materials (e.g. PLA, ABS), acrylic has a higher glass transition temperature of 110 °C, which prevents them from melting or thermal deformation during actuation. Acrylic leaves are manufactured by laser cutting using 8 mm thickness acrylic plates (see Fig. 4(a)). The size of the processed acrylic blocks measures 45 × 8 × 4 mm (Fig. 4(a1)). By combining 4 pieces of acrylic blocks hole-to-hole together, a 45 × 32 × 4 mm acrylic hinge leaf can be obtained. Every acrylic hinge weighs 5.4 g. Users can customize their own shapes with software such as Auto CAD and Solidworks.

Another material for making hinge leaves is cardboard. The cardboard hinge weighs 2.1 g, which is the lightest among the three different materials versions. Double wall cardboard is recommended, which has two layers of corrugated fluting and three liners (Fig. 4(b1)). Users can cut it with scissors or knives from package boxes, and tape can be used to enhance its edges to make it stronger and durable.

The third option is textile. Being similar to a sandwich, the textile hinge leaf consists of two layers of thick canvas fabrics with a middle layer of 0.2 mm thickness polypropylene (PP) film (see Fig. 4(c3)). These three layers are sewed together by several columns of thread. Space is left between every two thread columns, for inserting the split pins and SMA wires. Fabric with different colors or pattern can be selected, which can enrich the aesthetics of textile hinge leaves.

3.3 Other components

A split pin is also known as a cotter pin or cotter key which has two tines and one hole (see Fig. 1(c)). With the help of split pins, the actuation hinges can be assembled easily. Each hinge requires six split pins to fix two leaves and the SMA wires. More details about the installation of the split pins use can be seen in the section 4. Screws and nuts act as "rotation shaft" of the actuation hinges. The shape-changing objects can be actuated by hot water or applying an electrical current through the SMA wires (Joule heating). Electrical wires should be used to connect the SMA with power when the Joule effect approach is selected.

4 SHAPE-CHANGING OBJECTS CONSTRUCTION STEPS

The shape-changing objects construction process is divided into three steps, which are *SMAs pre-deformation, hinge construction* and *object body and hinge combination.*

SMAs pre-deformation. For the construction of *activate-to-open* hinge, a 180° *SMA wire A* should be selected and then deformed to 0°, so that it can combine with the 0° *wire B* easier (see Fig. 5(a)). Regarding the *activate-to-close* hinge, a *SMA wire A* with preset angle of 0° is used. It needs to be deformed to 180° before uniting with 180° *wire B.*

Hinge construction. Each actuation hinge needs six split pins and two pairs of screws and nuts. For the acrylic hinge leaves, the two tines of each pin can be split slightly before inserting into the acrylic bricks to prevent them from slipping out. As for the cardboard hinge leaf, the split pins can be clipped in the middle liner (Fig. 4(b1)). Similarly, the split pins can be combined with the textile hinge leaves by clipping them on the PP film layer (Fig. 4(c3) and Fig. 5(b)). Of the six split pins, two of them are used to help fix the SMAs and two rigid plates. As shown in Fig. 5(b), SMAs can thread through the pin holes before inserting into the plates, which can make the SMAs fix with the plates tightly. The constructed hinges based on three different types of materials and their details can be seen in Fig. 4(a5), (b5) and (c5).

Object body and hinge combination. The object body refers to the non-morphing parts of shape-changing objects (see Fig. 5(c)). Users can customize the object bodies with different types of materials (e.g.

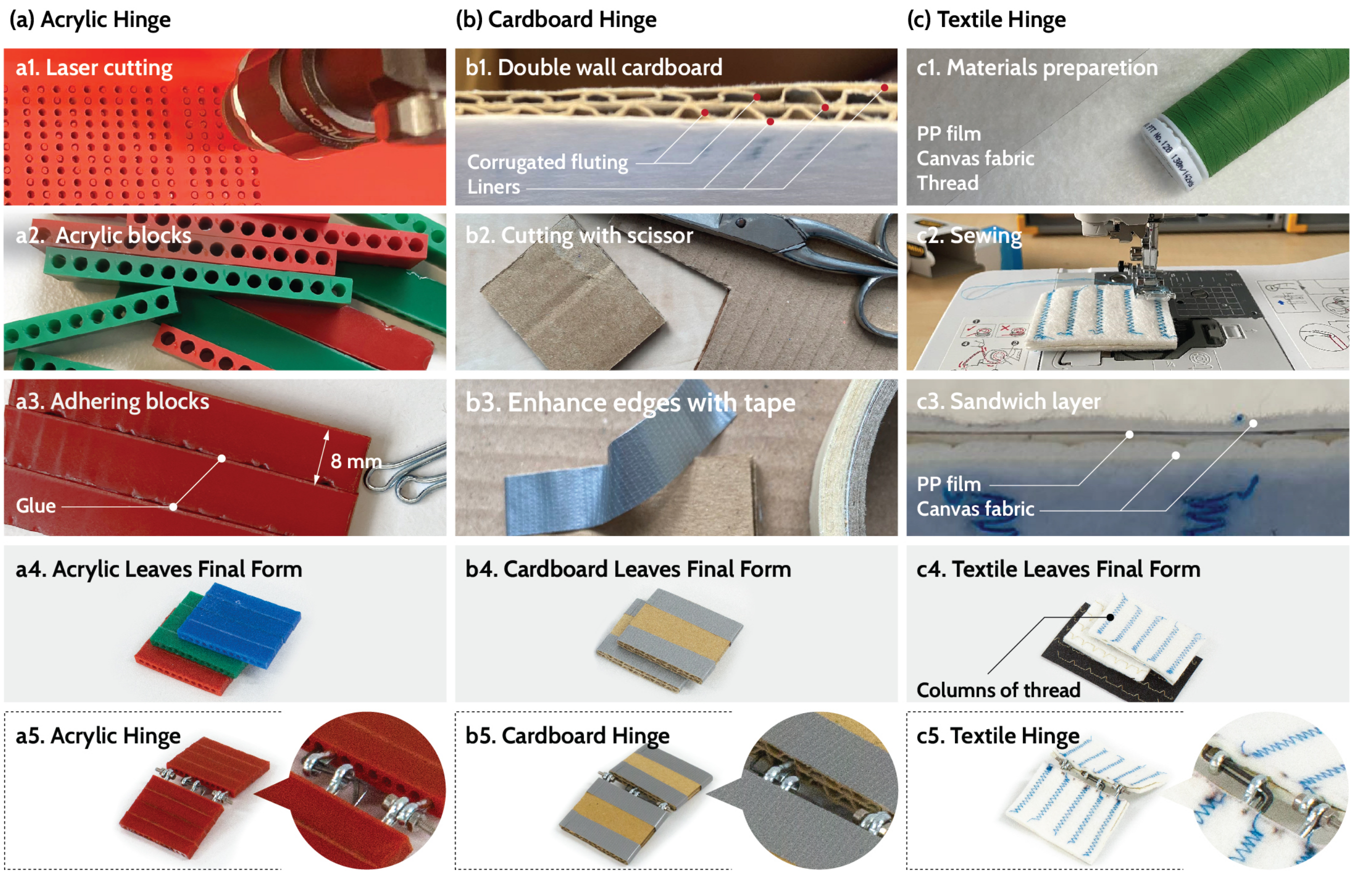

Figure 4: Hinge leaves based on three types of materials: configuration process and their structures. (a) Acrylic hinge leaves: acrylic blocks are manufactured by laser cutting, and then each four blocks are glued and combined together as a hinge leaf. (b) Cardboard hinge leaves: they are made from cardboard package box. (c) Textile hinge leaves: the sandwich structure leaves include two layers of fabric and one layer of PP film in the middle. Note that there is no limit of the type of fabric, but 2-3 mm thickness fabric is recommended. (a5), (b5) and (c5) show three types of hinge and their connection details. More details are explained in the *Hinge Construction* part of section 4.

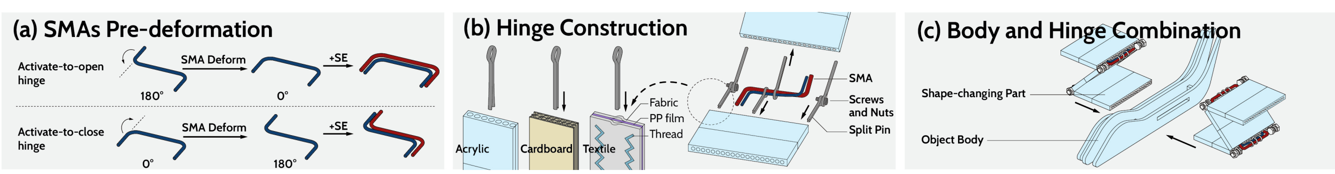

Figure 5: Construction steps of shape-changing objects. (a) The SMAs pre-deformation process is different depending on the selection of hinge type. (b) Hinge construction: the tines of the split pins can be inserted into the edge of the two hinge leaves, so as to form a complete hinge. (c) Acrylic hinges can combine with the object body by using superglue.

acrylic, cardboard, textile) according to their design concepts. The object body and the hinge actuators can be connected with adhesive (e.g. superglue, UHU 150 glue) or other approaches depending on the selected materials.

If the shape-changing object is expected to activate by electrical current, the torsion deformation part of the SMAs need to be connected with wires. Electrical wire and SMA are connected by wrapping the exposed copper around the SMA (Fig. 7(b) and (c)). If the actuation is done by placing in hot water, the electrical wire connection process can be skipped. It should be noticed that the hot water activation approach is inapplicable for cardboard and textile hinge leaves.

5 HINGE ACTUATION PERFORMANCE

5.1 Actuation force

A push-pull gage (Success MODEL ANF-200) is used to measure the actuation force. Prior to the measurements, a leaf of an *activate-to-open* acrylic hinge is securely attached using a fixture at its close state, and the push probe of the gage is placed and secured in contact with another leaf (Fig. 6(a)). When the hinge is actuated with 1.2 Amp, it tries to open but is blocked by the push probe, which can record the maximum actuation force during Joule heating. Experiments show a force range from 4.5-5.7 N. Considering the hinge actuator's lightweight (2.1-5.4 g), it is a considerable actuation force level.

5.2 Response Time

An *activate-to-open* acrylic hinge is used to measure the response time. The experimental findings indicate that when a current of 1.6 Amps is applied, the hinge takes approximately 4 seconds to reach its actuation angle. By increasing the current, the heating time can be reduced. For instance, if the current is increased to 3.2 Amps, the heating time is reduced to 3.5 seconds. However, in comparison to heating, the cooling process requires significantly more time, taking around 45 seconds at room temperature. To minimize the cooling time, it is advisable to increase the airflow speed [30] and maintain a lower ambient temperature. With the water-activation approach, the response time is shorter. It can be actuated in 76 ℃ water within 3.4 s and cooled down in 21 ℃ water in 4.5 s.

5.3 Durability

SMAs within the deformation limitation can be used for 10^4- 10^7 times without showing any fatigue [8]. For the hinge, the most common failure is when the pins slip out of the holes. Several experiments on 180° hinges in different materials are conducted to investigate how much force could lead to the failure. The push-pull gage is used again to measure the force. As shown in Fig. 6(b), the pull hook of the gage is bound to one leaf of the hinge by two ropes. The gage records the maximum force during one leaf is completely pull out from the pins. The finding indicates that it needs 5-7 N to separate two leaves of a hinge.

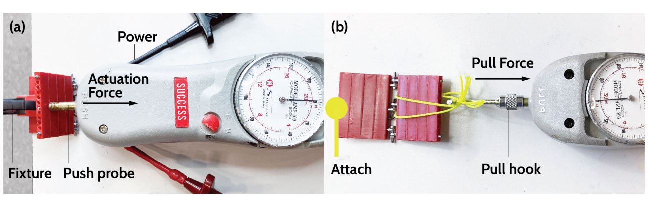

Figure 6: Hinge performance evaluation with a push-pull gage. (a) Actuation force measurement. (b) Tests of the durability of the hinges.

5.4 Energy Consumption

As shown in Fig. 7(d), a gripper constructed with 6 SMA hinges can be activated by 4 AA alkaline batteries in series (6 Voltages). Total energy (E) stored in these batteries is about 15 watt-hours. With a digital multimeter, the current is tested as 0.65 Amps, and the power (P) consumed by the actuator (during activation) can be calculated as 3.9 watts. The power for maintaining the activation phase is about 1.4 watts (tested by a DC power analyzer), which is only 36% of that of the activation phase. Therefore, if the microcontroller can reduce the passing current once the hinges are actuated, the time that 4 AA batteries can maintain 6 SMA hinges at its activation phase is about 10 hours. If less SMA hinges are used in shape-changing objects, energy consumption will be lower.

6 HARDWARE

A Bluetooth control module is developed, which enables users to control their shape-changing objects remotely. As shown in Fig. 7(a) and (c), hardware includes a Seeed Studio XIAO nRF52840, a Finder Relays 36.11.9.006.4001, a DC/DC converter and a 20V rechargeable power. All the SMA wires of the gripper need to be connected first (see Fig. 7(b)). The microcontroller XIAO integrates Bluetooth 5.0 connectivity. After pairing with another Bluetooth device (e.g. a mobile phone or laptop), it can receive signals from users. The electrical current can be toggled by the Finder Relays, which in turn is controlled by XIAO (see Fig. 7(a)). The DC/DC converter can handle the voltage of 8-30 V, and provide 1-12 V up to 8 Amps. The small copper screws on the top side of the converter are used to set the (maximum) values. In our cases, we set the maximum current to 2 Amps to prevent damage to sensitive control components. A simple website based on Python is developed, on which users can pair the Bluetooth of XIAO, activate the shape-changing object or cut off the current remotely.

Mimosa can also be combined with sensors to support more diverse electronic device designs. To demonstrate this, a distance-sensing triggered gripper is designed. Circuit connection can be seen in Fig. 7(d), in which 4 AA batteries are used as power supply. When the proximity sensor detects an item within 20 cm, microcontroller of the Seeeduino board can activate the gripper through MOSFET. The activation process can be seen in Fig. 7(e).

7 APPLICATION EXAMPLES

Robotics. An adaptable gripper is made by acrylic and six *activate-to-close* hinges. It is able to grip items with different shapes, such as eggs, a wire coil and a cupcake wrapper (see Fig. 8(a)). The gripper weighs 91 g, while it can easily grip the 596 g wire coil.

A rolling robot is constructed with an acrylic object body and cardboard hinge leaves (Fig. 8(b)). It is a cylindrical structure which includes four *activate-to-open* hinges. Each hinge has one leaf fixed to the object body (red cylinder in Fig. 8(b)), and a second leaf is bonded with two acrylic semi-circular pieces. When the hinge is actuated, the second leaf opens and pushes the robot to rotate forward. Four hinges are actuated sequentially. The rolling robot can move about 25 cm in approximate 10 seconds (with two hinges actuated sequentially).

Toys. An airplane and butterfly are constructed with acrylic plates, which can be activated with hot water or electricity (Fig. 8(c) and (d)). It can be seen that the SMA hinge actuator is small and has little influence on the aesthetics of shape-changing objects. Within the butterfly demonstrator, even each hinge leaf is glued

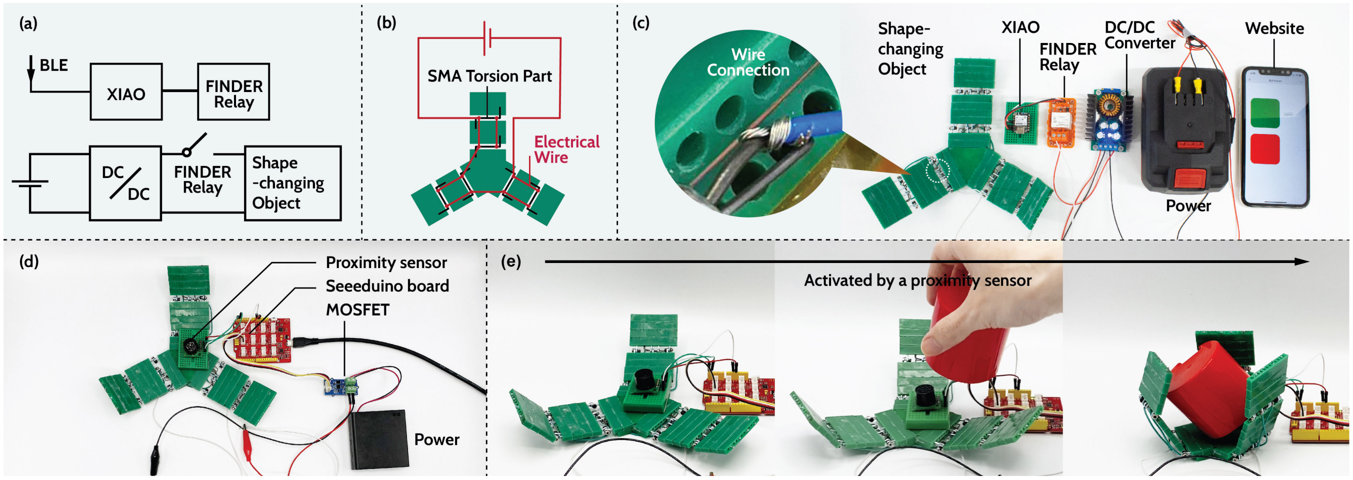

Figure 7: (a) Circuit diagram of the Bluetooth control module. (b) SMA wire connection of the gripper. The current needs to flow through all the SMA torsion parts. (c) Hardware for the Bluetooth control module. (d) Circuit connection of the distance-sensing triggered gripper. (e) Activation process of the distance-sensing triggered gripper.

with a big wing (150 × 130 mm, 44.3 g), 0.2 g SMA wires can still drive it to move.

Self-closing pocket. The self-closing pocket is made of textiles (see Fig. 8(e)). The flap is embedded with an *activate-to-open* hinge. The design idea is that it can prevent things from dropping out or being stolen at close state. Once it is activated, it can open automatically. The self-closing pocket only needs a battery of 1 V to be activated.

8 WORKSHOP STUDY

A workshop with 6 design students was conducted to evaluate the usability and versatility of the toolkit. By examining user-constructed shape-changing objects and participants' reflections on toolkit's application scenarios, we can access whether Mimosa can support creative practices. In addition, affective feelings after using the toolkit was investigated, and drawbacks of the toolkit were also identified for further improvement in our future work.

8.1 Set-up

The toolkit was placed on a large table in a room. *activate-to-open* and *activate-to-close* SMA hinges were provided. Hinge leaves were available in two types of materials: cardboard and acrylic. Participants can make their selections based on their design concepts and actuation methods (electricity or water). Other types of components such as split pins, screws and nuts, electrical wires, A4 size cardboard, 1mm thickness wood board, adhesive, etc. were provided in sufficient quantities. A camera was set up on a tripod to record participants' prototyping process with the toolkit.

8.2 Participants

6 design students including 4 master students and 2 PhD students were recruited for the workshop. They were divided into 3 groups. All of them do not have prior experience in using similar toolkits.

8.3 Procedure

The workshop began with an introduction session, in which participants got familiar with the components of the toolkit, prototype construction steps and methods of activation. Afterwards, they were given 15 minutes to think and discuss their prototypes. Once participants had concrete ideas, they can start constructing their prototypes in approximately 30 minutes. After finishing, they activated their prototypes to see whether the shape-changing processes could match their expectations. The workshop was completed with a questionnaire and post-study semi-structured interview on their experience of using the toolkit.

Four types of data were collected during the workshop study, including video recordings of the construction process, questionnaires, photos of final prototypes and notes from the interview part.

8.4 Findings

Findings of the workshop study are divided into three parts, which are *user-constructed shape-changing objects, analysis results of the questionnaires*, and *observation and interview reflections* which summarized from the workshop constructing session and the post-study interview.

8.4.1 User-constructed shape-changing objects. Group A (P1 and P2) designed a playful interaction toy, *caterpillar*, with 6 acrylic hinges and two customized cardboard shapes, on which they drew a cute face and an green apple (see Fig. 9(b)). They expected that when it was actuated with electricity, the *caterpillar* can contract its body (into a zigzag shape) toward the apple. However, they did not take the hinge flipping motion (clockwise or counterclockwise) into consideration when placing the nitinol wires into the hinge leaves. The *caterpillar* changed to an "O" shape when it was applied electric current, as all hinges flipped counterclockwise (Fig. 9(b)).

Group B (P3 and P4) constructed an interaction device *Thumbs Up*, which composed of a cardboard palm and a thumb, connected

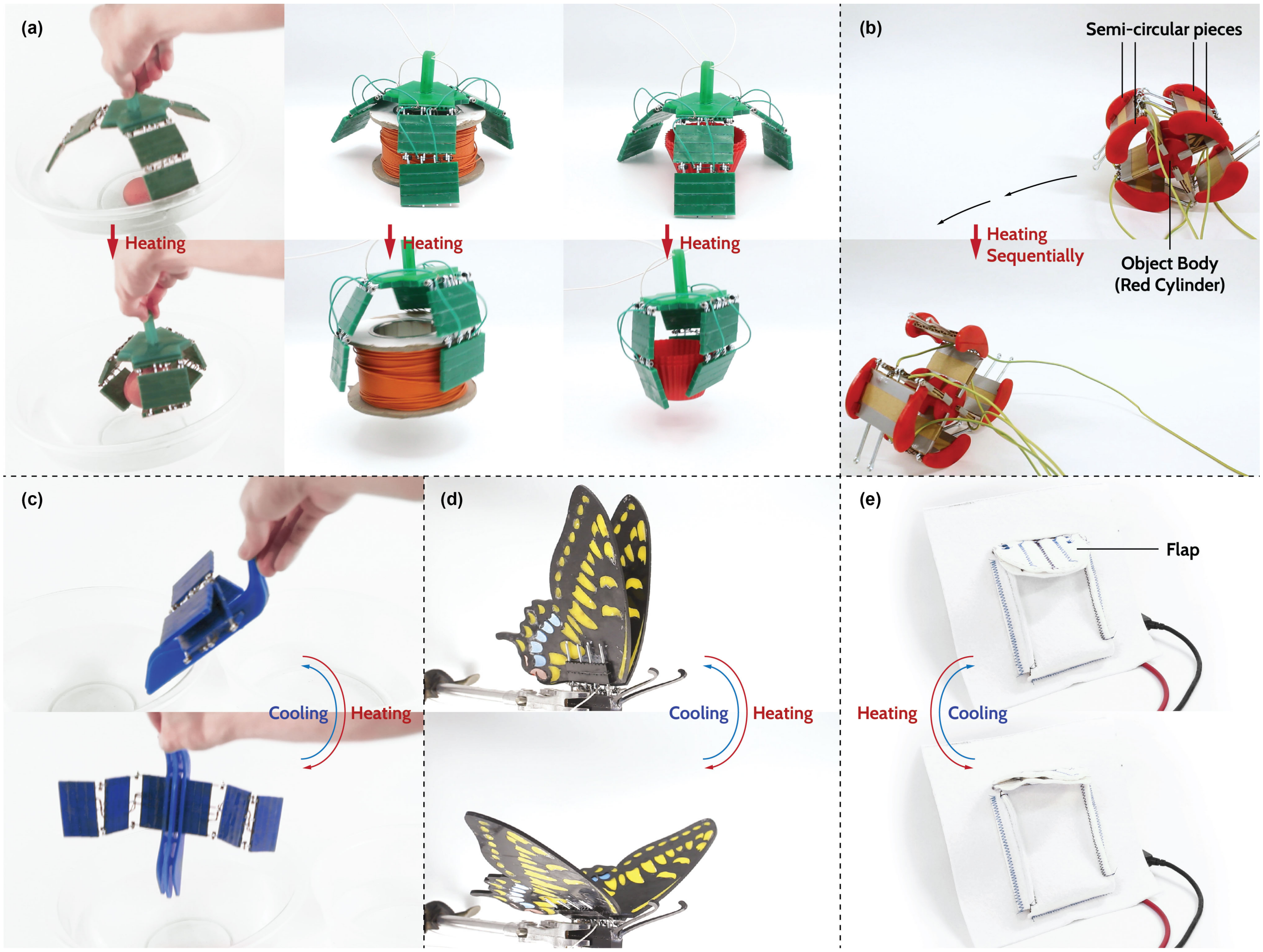

Figure 8: Applications of the toolkit. (a) An adaptable gripper; (b) A rolling robot; (c) An airplane; (d) A butterfly; (e) A self-closing pocket.

by an *activate-to-close* actuator (Fig. 9(c)). The concept of *Thumbs Up* was that it can be linked to social medias, and activated when friends give "likes" on posts or messages. It was the group that used cardboard only without acrylic material, and the hinge leaves were all made into customized shapes instead of using the provided rectangular hinge leaves.

In contrast with the previous two groups, Group C (P5 and P6) developed "*Liang Ting*", which is an architecture design concept for children. *Liang Ting* is a traditional Chinese pavilion that serves as a sheltered outdoor resting place, providing a cool and pleasant area for relaxation and social gatherings. It was made with a cardboard support column, a roof, a cardboard hinge actuator, and four red *activate-to-open* acrylic hinges (Fig. 9(d)). *Liang Ting* was expected to actuated by environment temperature, instead of electricity or hot water. P5 explained that "*in high temperature environment, like summer, the hinges on the roof can open automatically, expanding the shading area*".

To summarize, the three user-constructed shape-changing objects were developed for different purposes (toy, interactive device and architecture design), which indicates the versatility of the toolkit.

8.4.2 Analysis results of the questionnaires. With the analysis results of the questionnaires, we find that almost all participants thought the toolkit can inspire them to design, which reveals that Mimosa can support creative practices. In addition, it seems that the toolkit is not easy to use. Even though, participants' affective feelings were quite positive after using the toolkit. They especially felt "*amused*", "*enchanted*" and "*pleased*". More details can be seen in the appendix A2.

8.4.3 Observation and interview reflections.

(1) Difficulties during the construction process. As we observed, difficulties were discovered at every construction step. At the first step, *SMAs pre-deformation*, Group C cannot distinguished which

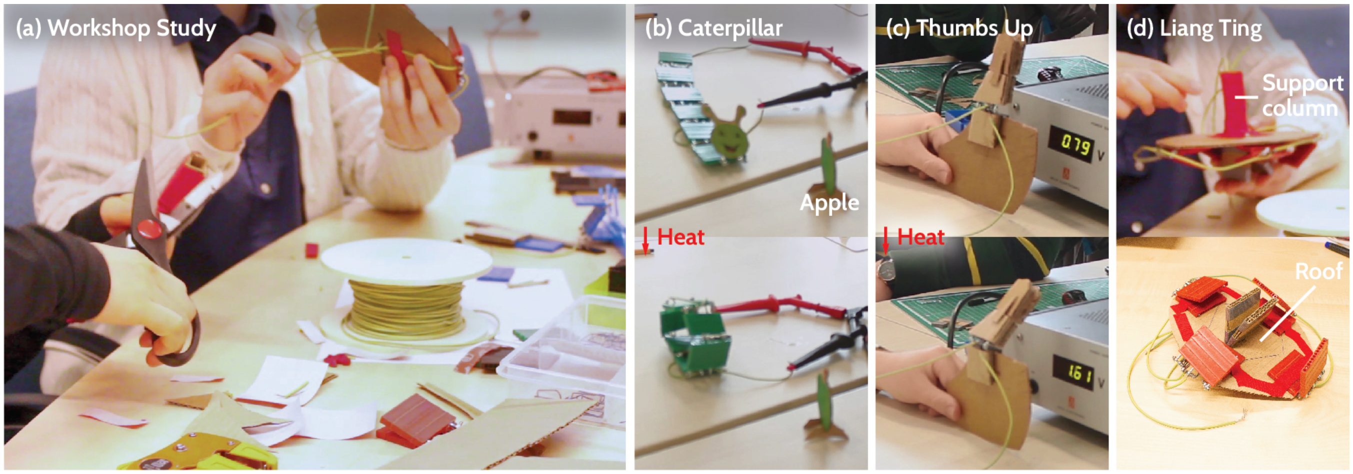

Figure 9: (a) Workshop photo; (b) *Caterpillar* constructed by Group A; (c) *Thumbs Up* from Group B; (d) *Liang Ting* made by Group C.

SMA wires were for the *activate-to-open* hinge, and they asked for help. For the second step *Hinge Construction*, Group A and C had difficulties at inserting the split pins into the holes of acrylic hinge leaves. They also reflected this in the interview session. It is because each acrylic hinge leaf was glued by four acrylic block (see Fig. 4(a)), and the deviation between holes of each two blocks could make the pins stuck. In addition, Group B messed up with the flipping direction of the hinge actuators, which leaded to an unexpected changing shape as stated in section 8.4.1. Group C also thought that the construction process was fiddly. In the final step, *body and hinge combination*, Group B used lots of superglue to bond the cardboard. The superglue was not strong enough and could soften the cardboard because it is mainly for plastic and glass use.

(2) Engagement during the crafting process. Participants showed a high level of engagement during the crafting process. They enjoyed collaborative discussions and sharing their creations, such as the *caterpillar facial expression* and *thumbs shape*. They delighted and playfully teased each other, fostering a relaxed and enjoyable atmosphere throughout the workshop.

(3) Affordances of the toolkit. Group A obtained the *caterpillar* as they planned finally. Even though they messed up the flipping direction of the hinge at the first time, the modular design of the toolkit allows them to disassemble and reconstruct the *caterpillar*. Group B planned to make a thumb that moves in the anterior-posterior direction. However, this was not possible due to the limitation of the SMA torsion length (Fig. 2(a)). They had to change their plan and made the thumbs move in the left-right direction. Group C did not have a concrete plan before constructing, just with a concept of *Liang Ting*. They discussed and made the shape-changing object at the same time. For example, P5 thought "*An octagonal roof is better than the square shape. And we miss a column*". Then they began to cut the square roof into an octagonal shape and constructed the column with cardboard. This indicates that Mimosa's modular design and compatibility with cardboard offer effective affordances. However, the provided SMA materials might impose certain limitations on its affordances.

(4) Cardboard supports customization. All three groups used cardboard to construct their shape-changing objects. Cardboard serves as a versatile medium in the toolkit. Its unique properties of being easily cut and shaped allow users to customize and craft their desired forms. As a result, the cardboard becomes a platform for creativity, enabling a diverse array of shape-changing objects to be brought to life by users' artistic expressions. Group A capitalized on the distinctive attributes of cardboard, including both cutting and drawing. Before the activation of *caterpillar*, when the cardboard green apple was knocked over, P2 was anxious and said "*Oh wait, my apple should be there!*". She gestured for us not to activate *caterpillar* until she stood it. We learn that P2 really valued the importance of the customized cardboard, which could make their *caterpillar* come alive.

(5) Application scenarios. Participants were asked about the application scenarios of Mimosa in the interview session. P1 mentioned its application in the "*technical lessons of school*". P2 said that it can be used as a validation toolkit in "*shape-changing furniture or fashion industry*". P3 and P5 saw great potential for this toolkit to be developed into "*playful toys*" and "*artistic interaction devices*". In addition, P5 and P6 especially liked the temperature-activation properties of the hinge actuator, which can "*make it sustainable*" (P5). For example, P5 described that "*a laptop stand which made of the SMA hinges could be activated and then lift up the overheated laptop automatically without applying electricity*". P6, who has a research background on sustainable circular packaging systems, mentioned that the hinge can be "*triggered by food heat*", and used in "*temperature-controlled containers for food preservation*". In summary, participants' reflections on the toolkits applications cover a variety of fields, including education, entertainment, fashion, furniture and food industry. P5 and P6's feedback about sustainability is

beyond our expectation, which is also definitely another benefit of the toolkit.

9 DISCUSSION, LIMITATION, FUTURE WORK

9.1 Mimosa supports creative practices

As mentioned in the introduction, to develop a toolkit which can support creative practices, we selected 4 metrics as design principles of Mimosa, which are *usability, transparency, quality* and *agency*. Taking into account the insights gained from the application examples and workshop study, we critically examine whether our toolkit conforms to these metrics.

Usability. We try to lower the threshold of shape-morphing objects construction by combining simple and easily obtainable components in the toolkit. Application examples and user-constructed shape-changing objects indicate the *usability* of Mimosa. Although on the Likert scale regarding the difficulty of using toolkits, almost all participants chose the medium level (see Appendix A2), they all succeeded in making fully functional demonstrators in 30 minutes, which is a very short time in compared with the existing similar toolkits (e.g. four hours of Jie's work [43], a full day of *ShapeClip* [15]).

Transparency. In contrast to motor-based or pneumatic-based shape-changing toolkits, Mimosa can be defined as a *less transparent* toolkit, as the working principle of SMA is more complicated, and the method of activation is much more diverse. Even though essentially the SMA is activated by heat, the heat source can come from Joule effect, environment temperature (e.g. outdoor temperature in summer (P5), hot food (P6)), or even body temperature [14]. The complexity of SMA (less transparency) could bring confusion or challenges of construction when using Mimosa (refers to section 8.4.3 (1)), but the diverse activation approaches can unleash greater potential in more complex designs (section 8.4.3 (5)). This discovery is consistent with the previous HCI research, which shows that a *less transparent* tool enable more creative and innovative shape-changing objects [34].

Quality. Analysis result of Q2 in Fig. 11(a) reveals that the not all participants expectations were fulfilled, whereas their affective feelings were quite positive after using Mimosa.

Agency. We enhance Mimosa's *agency* by incorporating everyday materials (e.g. cardboard and textile) that encourage creativity and craftsmanship. Research shows that engaging users in tangible user interfaces through crafting can help to develop personalized devices [18, 19, 40, 44]. User-constructed shape-changing objects and participants' feedback on the toolkit's application scenarios indicate the *high agency* of Mimosa.

9.2 Opportunities of connecting crafting circuits research

Electrical wires need to be used to connect SMA of the hinge actuators when the electrical heating method is selected. P2 reflected that "*when we use many hinges, it is fiddly to connect wires with SMA*". This prompts us to reflect on how to optimize the wire connection process. We think conductive ink and thread could be potential solutions.

David et al. developed simple and robust techniques for drawing circuits with conductive ink on paper, enabling off-the-shelf electronic components to be embedded directly into interactive artifacts [35]. Similar works can be found in [17, 23, 39, 63]. In addition to paper and plastic, Clement et al. proposed a method to instrument existing glazed ceramic ware with interactive electronic circuits [68]. With these approaches, it is possible to draw circuits on cardboard, or print conductive ink onto future ceramic hinge leaves. It is expected that all SMA wires from different hinges in a prototype can be connected together once the construction process is completed, and no more exposed electrical wires are needed (except the wires which are required to connect with power). Textile-related toolkit research refers to [41, 56], in which modular electronics and conductive thread could be valuable reference for future upgrade of the textile hinge.

9.3 Limitations and future work

Toolkit components. The toolkit includes four types of SMA wires, which could confuse users when they need to select the right ones to construct the hinges, because all SMAs have a similar look. It could be better if SMAs are coated in different colours to distinguish each other.

The current hinge leaves of the toolkit only consists of three types of materials. To encourage more diverse handicraft and support creative practices, it is better to enrich the material selection by adding more options such as corrugated plastic sheets, hard foam and ceramics. Thin textile or materials like PLA that melt below the activation temperature of the SMA are not suitable for being used to make as hinge leaves. The diversity of materials also brought challenges and differences to the design process of the shape-changing objects. For example, if the thick textile materials are selected, sewing machines and scissors are useful tools for the constructing process, while for acrylic materials, superglue can be used for pasting, and laser cutting machines are required if users need to customize acrylic shapes. Users can also combine more than one type of material into a shape-changing objects (e.g. Fig. 8(b)), but then they need to consider and choose a suitable adhesion method between different materials according to their design concepts. In the workshop, we only used acrylic and cardboard, and did not study the the influence of material diversity on the construction process and users' experience. In the future, we will address on this, and might develop guidelines to help users select and construct with different materials.

Construction process. After the step of *pre-deforming the SMA wires*, users might mix up the flipping direction of the hinge (Group A). An approach should be presented in the future to help users with this issue. In addition, The connection method of the SMAs and hinge leaves will be redesigned to improve its usability.

Hardware. Only a Bluetooth remote control module and a distance-sensing triggered gripper are developed at this stage. If Mimosa can combine other sensors, it will show much more possibilities in different scenarios. As discussed in section 9.2, connecting the existing crafting circuits research can reduce the reliance on electrical wires, which can also enhance the aesthetics of the constructed shape-changing objects.

User study. The textile hinges and hardware have not been tested by users. It should be done in future work. Additionally, with 6 participants from the design field, the workshop study may lack sufficient quantitative data for very robust conclusions. In the future we will involve different target groups, e.g. school children, to find out if the current toolkit and construction set need further refinement.

Shape-changing capacity and response speed. The current toolkit only provides the bending motion with the SMA hinge. Other types of motions like linear and rotary motion should be considered to increase the versatility of the toolkit. The response speed of SMA hinge is slow in comparison with pneumatic and motor-based actuators, which could limit their application scenarios. For example, the toolkit might be ineffective for developing some VR haptic devices which have high requirements for latency control, or a robot hand with fast moving fingers. Using small diameter SMA wire can reduce the cooling time, but the actuator force of the thinner wires is smaller.

10 CONCLUSION

We present Mimosa, a constructive toolkit for creating shape-changing objects. A key component of the toolkit is the reversible hinges based on shape memory alloy technology. The SMA hinges can provide relatively high actuation forces. Moreover, they are lightweight with a small form factor, and thus have minimum effect on the aesthetics of the constructed shape-changing objects. The hinge leaves are provided in three types of materials, including acrylic, cardboard and textile. The high compatibility with everyday materials offer users space for creation. User can customize personalized shape-morphing objects through handicraft. Related hardware is provided, which demonstrates that users can control the shape-changing objects remotely, and the toolkit can combine with sensors to support electronic device design. Application examples in the field of robotics, toys and smart clothing are presented.

Mimosa aims to inspire designers to create their shape-changing objects with SMAs and everyday materials like cardboard and textile. Workshop study showed that the toolkit is indeed can support creative practices and provided a good user experience.

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A APPENDIX

A.1 SMA training process

The SMA used in the toolkit can be obtained through the SMA training process, as depicted in Fig. 10. Straight SMA wires can be purchased from material suppliers. To prepare them, the SMAs must be bent into either a 180° or 0° angle, by using a bending plier. Then, the wires should be affixed to a fixture using screws before being placed inside an oven (with a predetermined temperature of 500 ℃). It is important to ensure that the SMA wires are tightly secured on the fixture. After baking for 30 minutes, the fixture can be removed from the oven and placed into cold water for cooling purposes.

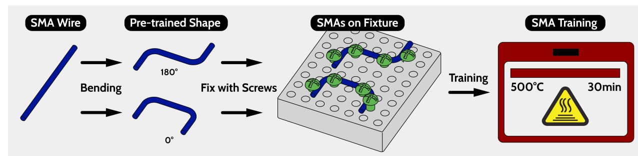

Figure 10: SMA training process

A.2 Analysis results of the questionnaires

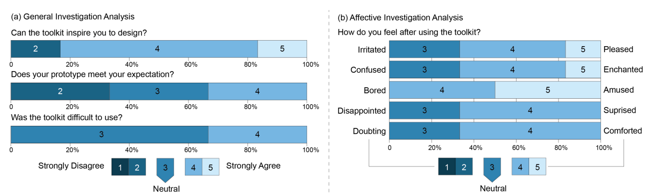

Figure 11: Analysis results of the questionnaire. (a) General investigation analysis; (b) Affective investigation analysis.