PITAS: Sensing and Actuating Embedded Robotic Sheet for Physical Information Communication

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ABSTRACT

This work presents PITAS, a thin-sheet robotic material composed of a reversible phase transition actuating layer and a heating/sensing layer. The synthetic sheet material enables non-expert makers to create shape-changing devices that can locally or remotely convey physical information such as shape, color, texture and temperature changes. PITAS sheets can be manipulated into various 2D shapes or 3D geometries using subtractive fabrication methods such as laser, vinyl, or manual cutting or an optional additive 3D printing method for creating 3D objects. After describing the design of PITAS, this paper also describes a study conducted with thirteen makers to gauge the accessibility, design space, and limitations encountered when PITAS is used as a soft robotic material while designing physical information communication devices. Lastly, this work reports on the results of a mechanical and electrical evaluation of PITAS and presents application examples to demonstrate its utility.

CCS CONCEPTS

• **Human-centered computing → Ubiquitous and mobile computing systems and tools**.

KEYWORDS

shape-changing interface, physical telecommunication, phase transition actuator

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1 INTRODUCTION

The field of soft material-based actuators and shape-changing interfaces is young, yet rapidly growing. It has taken root to broaden supporting mechanisms and technologies, inspiring much cross-domain research. Although shape-changing interfaces can support adaptive, flexible interactions within unpredictable real-world environments, one long-standing challenge is the lack of rapid prototyping methods that can be used to create such interfaces. Making soft robotic materials that can sense, self-actuate, and produce large macroscopic deformations requires a considerable amount of technical setup, which further limits the system designs from being compact and narrows the range of applications for untethered systems [31, 35, 68]. In addition, applying sensing capabilities to hyper-elastic elastomeric matrices requires expensive machine setups or complicated fabrication steps (*e.g.,* directly 3D printing embedded strain sensors or creating micro-channels filled with conductive liquid metal for pressure sensors [38, 47]).

To overcome these challenges, we present PITAS, a "robotic material" sheet, consisting of a sensing/heating layer and an actuation layer. When heated, the ethanol embedded in the actuation layer boils once it has reached the liquid-gas transition temperature, leading to a volumetric expansion, but does not require external regulating systems, and will reverse back to its original shape as its temperature returns to ambient levels [35]. The goal of this paper is to present a rapid and accessible prototyping method that can be used to create reversible soft-material-based systems.

PITAS integrates both input sensing and active shape output within a single sheet, and this soft silicone-based system endows PITAS with great adaptability to different materials (*e.g.,* thermochromic pigments, tactile add-ons) for different purposes. Additionally, the bottom conductive layer makes PITAS system "heating ready", so one can simply attach electrodes selectively for different swell sizes or locations. The generic robotic sheet form factor and the associated cutting fabrication approaches further enable applications ranging from making 2D-3D shape-changing artifacts to augmenting everyday objects. Within the wide range of applications, PITAS can also go beyond a single space to convey physical information across multiple locations. Prior work has demonstrated that materiality plays a critical role in emotional interactions – how we perceive, interpret, and feel about information [21, 61]. So, we also investigate how non-expert makers could create their own physical telecommunication devices, as well as explore the unique and feasible affordances PITAS can provide.

Although PITAS is a custom synthetic sheet that was prepared in the lab, it would be possible to mass-produce the sheets to make them widely available in electronics or craft retail stores, especially given the simplicity of the sheet fabrication process. Like copper tape or other craft sheet materials, those who enjoy DIY-making projects could purchase a roll and use it as needed, apply widely available cutting methods, and connect it with existing electronics and hardware parts for self-sensing and actuating projects.

The main contributions of this paper are:

- A novel, reversible, sensing and actuating embedded "robotic sheet" that is based on a phase transition mechanism that produces large macroscopic deformations.
- Technical details about PITAS that include the design spaces for applying the sensors and actuators, fabrication methods, and the mechanical/electrical properties.
- Application examples that demonstrate how PITAS can be implemented and used during different scenarios.
- A user study to validate the usability of the PITAS system and explore the potential design space.

2 RELATED WORK

2.1 Shape-Changing Interfaces

Soft material-based shape-changing interfaces which can dynamically change their orientation, form, volume, texture, or stiffness, has been an emerging area within HCI [14, 54, 60]. Researchers have made tremendous developments [3, 46, 50, 57, 73], mainly due to their ability to serve a wide range of users [69, 73], adaptability to various form factors [39, 55, 63], and diverse functionality [28]. Researchers have also demonstrated how their versatile sensing abilities can be combined with different types of actuation mechanisms, including sensing for pneumatic actuators [43, 65], shape memory polymers [69], shape memory alloys [51]. There are also other works that are presented as tool kits or parametric design interfaces for more general purposes [15, 20, 48, 67]. Although there have been advancements in the sensing and actuation mechanisms of soft material shape-changing interfaces, current methods are still in their infancy and are limited. Electroactive polymers, for example, are capable of providing high-frequency locomotion but usually require pre-processing of the materials (*e,g.,* uniform pre-stretch of the material) and high voltages to trigger the actuation [7, 31]. Pneumatic-based shape-changing interfaces, which utilize commodity materials and electronic components to provide large strains or forces with rapid response time, require external compressors and pressure-regulating components, limiting their miniaturization and practicality for untethered applications [29, 68, 73]. Our PITAS system seeks to tackle these existing drawbacks by having an actuating and sensing embedded sheet that is easy to store for reuse, capable of providing large deformation, and requiring minimum hardware components [35].

2.2 Haptic Devices For Information Delivery

During the most recent years, haptic devices that can deliver different modalities of information are rapidly developing. They are showing potential in assisting a wide range of fields, including VR/AR [13], mobile devices [24] or wearables [17]. Many of these haptic devices have different form factors. For example, researchers have presented a jacket embedded with an array of pneumatically-actuated airbags and force sensors that can provide precisely directed forces and high-frequency vibration effects for virtual reality applications [11]. Similarly, *PneuHaptic* is a pneumatic-based bracelet that can trigger a range of tactile sensations on the arm by alternately pressurizing and depressurizing pneumatic chambers [17]. Researchers have also explored different types of materials that can be used to convey haptic information such as thin and flexible shape memory alloys (SMA) [16], self-contained retractable wire systems [13] and piezo-based interfaces for electro-tactile output on users' fingers [72].

2.3 Physical Telecommunication

As the travel distance increases, the demand for connection between individuals across multiple locations is also increasing, which leads to the productions like phones or online collaborative platforms. Many researchers have demonstrated how physical telecommunication can enrich the complexity of information or feelings that one experiences when located remotely [30, 32, 41]. One of the main focuses for physical telecommunication research has been on wearable telepresence systems. The local and remote users are commonly sharing the same vision or tactile experience to enable co-participation with each other [10, 18, 23, 27, 56]. These wearable devices are also manufactured and presented in various form factors like wearable cameras [25], helmets [64], or neck-worn devices [34]. *Physical telepresence* showcased several promising examples of remote collaboration, including remote shape rendering, PCB board soldering, or object movement manipulation [30].

2.4 Highly-accessible Soft Fabrication

Various fabrication techniques have been proposed to support the creation of soft material-based devices including soft lithography [52], mold-casting [73], laser cutting and stacking, and 3D printing [53, 70]. We mainly choose fabrication systems that are highly accessible. With the development of hobbyist digital fabrication equipment such as vinyl cutters [1], personal laser cutters [49] and dispensing-based 3D printers [2], users can fabricate our PITAS system in various more accessible ways.

3 SYSTEM OVERVIEW

PITAS is a sensing and actuating embedded synthetic sheet that is capable of conveying different types of physical information about **shape**, **temperature**, **color** and **texture** to users (Figure 1). The fabrication method starts with a simple pre-processing of the material (*e.g.,* mixing the phase transition material and the

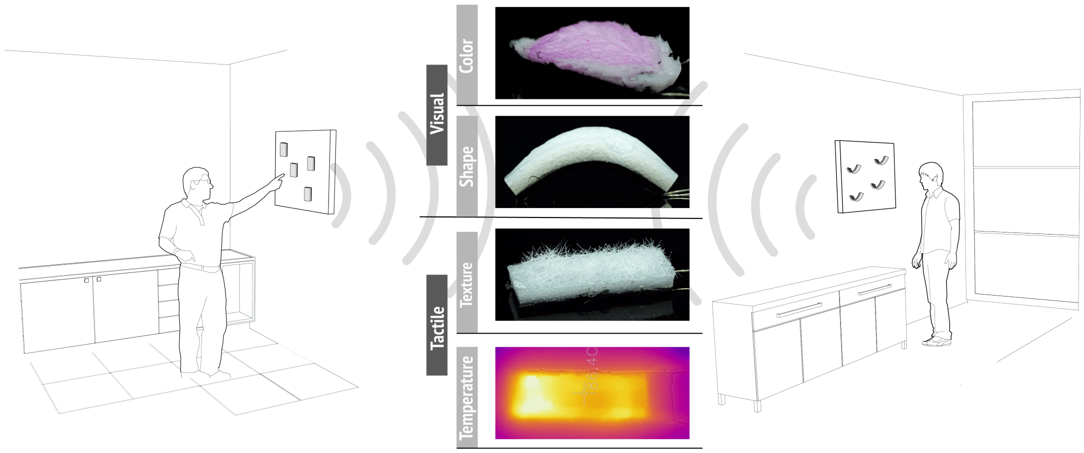

Figure 1: Overview of the PITAS system.

conductive silicone). The focus is on transforming the materials into a synthetic thin-sheet form factor after pre-processing them because sheets are easy to store and reuse. It also enables novice users who don't have mold-casting experience or 3D modeling knowledge to explore making sensing and actuating devices by manually cutting the sheets or utilizing a commodity vinyl/laser cutter. For those who want to investigate more advanced 3D shapes, PITAS also supports the use of 3D printing as an optional fabrication method. Commercially available components (*i.e.,* ESP32, relays, and a portable router) were mostly used to build the hardware system in this paper to provide a cloud server for communication, and a mobile app to visualize the transmitted data.

4 FABRICATION PIPELINE

4.1 Overall Fabrication Process

Soft material for soft actuators [35] has introduced a new type of phase transition actuating mechanism, which was adopted for our PITAS system. Illustrated in Figure 2 a, two-part platinum-catalyzed silicone elastomer smooth-on Ecoflex 0050 was chosen as the matrix material. Because of its excellent wettability with ethanol, it allows the system to maintain ethanol from escaping after curing, which also ensures an even distribution of the ethanol within the silicone matrix. The main form factor of the system in the existing work is relatively bulky, which limits the response time of the system [35, 36]. Also, the existing mold-casting approach can lower the motivation for the real users to use them since they have to prepare the material every time. Another issue for the existing method is using the Ni–Cr spiral wire to heat the system, where the placement of the rigid resistive heating wire became a critical challenge for the system design. Here, we propose a new way of utilizing this system by pre-making the phase transition actuator into thin sheets with a desired thickness (*e.g.,* 1mm-5mm) and pre-making another thin sheet of conductive silicone material (*e.g.,* 1mm), and utilize an instant conductive glue that we made to stack the sheets together to form a new "robotic material" sheet. For making the phase transition actuator sheet, 20 vol% of ethanol was first hand-mixed with 40 vol% of Ecoflex 0050A by using a stirrer for 2-3 minutes, and then with 40 vol% Ecoflex 0050B. The entire matrix will take approximately 3 hours to cure, and the material cost is 3 cents per gram. For the heating/sensing layer, we utilize the 3 wt% of Tuball 602 to mix with 48.5 wt% Ecoflex 0050 A and B by using an overhead stirring machine. We have also detailed the sheets preparation process in Figure 2 e.

4.1.1 Working Mechanism. The fundamental working mechanism is that ethanol, as the core actuating material, spreads inside the silicone matrix and forms bubbles occupied by ethanol vapors and air. When heating the material over its boiling temperature of 78.4 °C, ethanol boils and the local pressure inside the bubbles grows, forcing the elastic silicone elastomer matrix to comply by expansion to reduce the pressure. Since the new composite material contains conductive silicone layers, users can directly use this layer as the heater to heat the system. Meanwhile, another big advantage for this layer is that we can also utilize this layer as the sensor to sense input from users (*e.g.,* touch, press, slide). Additionally, we have also considered using Novec 7000 as a replacement for ethanol, which is an engineered fluid with a much lower boiling point (34 °C) from 3M company and has been used as a popular candidate for phase transition actuators [42]. However, the high air permeability for Ecoflex 0050 made it incompatible with Novec 7000, which will start to degrade during the mixing/curing steps and most of the liquid will escape from the matrix after 2-3 hours [45]. A latex membrane or Teflon sheet instead of Ecoflex 0050 should be applied as barriers/container to cover the device [19].

4.1.2 Actuator Design Space. The PITAS system combines both sensing and actuating layers, making it a great platform for providing diverse inputs and outputs. We have mainly focused on making design choices not only based on PITAS's shapes or motions but what physical information PITAS can enable. We have showcased four categories of design primitives of PITAS, including shape, color, temperature, and texture, which are selected to represent different visual or tactile information that PITAS can deliver.

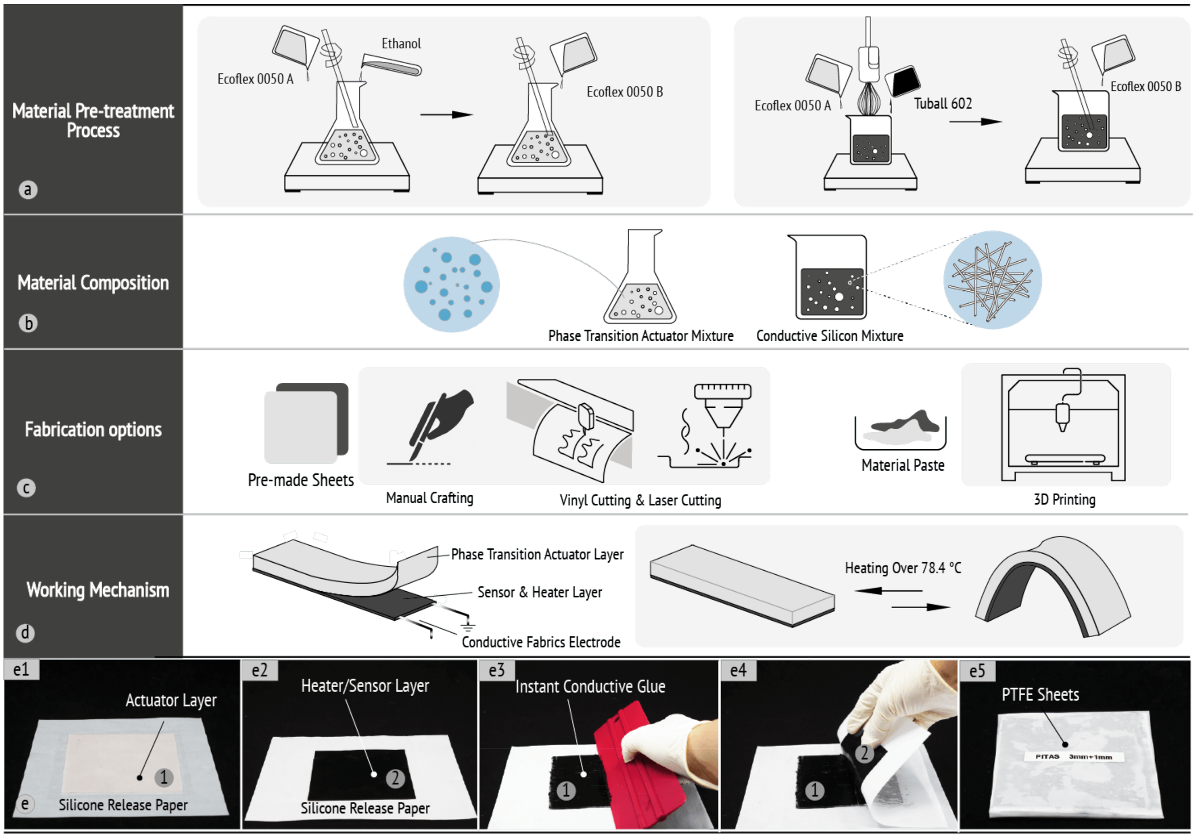

Figure 2: (a) Material preparation steps for phase transition actuator and conductive silicone; (b) The material composition; (c) The two available fabrication options: 2D cutting & 3D printing; (d) The fundamental working mechanism for the system; (e) Detailed fabrication process.

We also would like to note that these actuator examples are inherently based on the same heating/actuating mechanism for PITAS while endowing it with different additions (*e.g.,* thermochromic pigments, tactile add-ons) and are entangled with each other. In Figure 3, we have shown: (1) Shape primitives: PITAS can be cut into various thin-sheet shapes to form different 2D shape-changing modules or layered up to assembly 3D structures where people can control each layer locally, or combine with other materials as an additional layer or geometric extensions (*e.g., paper*). (2) Heating primitives: On the same sheet, PITAS can be triggered selectively. For example, the first three primitives under the heating category are of the same size, but by alternating the location of the electrodes, one can achieve different swell sizes of PITAS, while for the rest examples, one can also choose to selectively trigger different spots of PITAS for different types of deformation. (3) Color-change primitives: PITAS is a heating-based system, making it a perfect system to combine with thermochromic pigments to leverage visual information communication. We show how to enable the deformation and the color change at the same time. (4) Surface texture primitives: With the unique advantages of silicone's adaptability, we show how we can simply alter the PITAS' surface features to enhance the tactile information it can communicate.

4.2 Sensor & Heater

There are many existing methods to make conductive silicone, including creating channels for embedding conductive liquid, mixing with carbon nano-tubes or carbon fibers. However, to maintain the simplicity of fabrication and utilize the most accessible materials/tooling, we only considered methods that do not involve multiple steps of chemical synthesis or require machines that are not highly accessible.

Mixing with carbon nano-tubes and carbon fibers became the optimal options, which have both been adopted by the HCI community [44, 74]. Between these two material options, carbon fiber will dramatically reduce the stretch-ability of the silicone, so carbon nano-tubes show a greater potential. We used Tuball 602, which is a commodity graphene nanotube-formulated conductive filler specially designed for making conductive liquid silicone rubbers (LSR). We chose these specific carbon nano-tubes for the following reasons. First, it provides fine dispersion of nanotubes in the host matrix. Second, it's commercially available at a low price (35 cents per gram). Third, it requires low dosages (0.3 wt%-5 wt%) which also reduces the effect on the softness of the silicone. Finally, it comes as a paste form instead of powder which reduces the inhalation safety concern for the material.

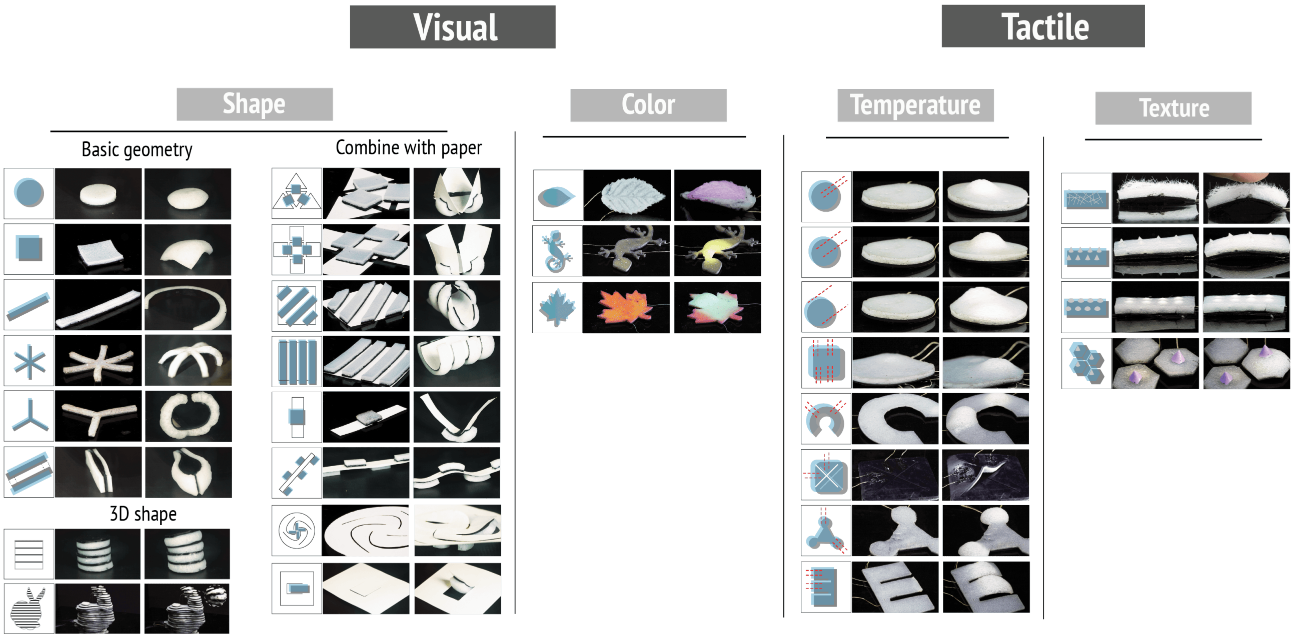

Figure 3: Four categories of PITAS design primitives.

4.2.1 Sensing Modalities. In Figure 4, we present different sensing modalities. It is noteworthy that we used a vinyl cutter to cut the different shapes of the sensors shown in Figure 4 b-c within one path. Our sensing modalities are mostly based on two commonly used sensing techniques: resistive sensing and capacitive sensing. Figure 4 b shows two methods of resistive sensing including stretching and bending, and Figure 4 c shows three methods of capacitive sensing including simple touch, pressure sensing and sliding. We have also included the continuous raw data for both resistive (stretch) sensing and capacitive (touch, press) sensing in Figure 4 e. The resistive changes from e1 are read from a two-probe multimeter and the Capacitive Sensing Library of Arduino is used to read the capacitance change raw data for e2 & e3.

4.3 Instant Conductive Glue & Electrode

The bonding of soft material interfaces with electrodes is always troublesome because of the high deformability and local fragility of the material. Researchers have tested a wide range of connection routines such as silicone glues for pneumatic systems, silver epoxy or liquid metal (EGaIn) for printed electronics, and soldiering paste for shape memory alloy (SMA) systems [6, 8, 26, 37, 62]. However, most of the current connection methods are either not deformable (*e.g.,* silver epoxy) or can cause leakage (*e.g.,* EGaIn). We have developed an instant conductive glue made of Ecoflex 0035 fast. We mixed the 0035 fast A with 4% of Tuball 602 for 30 min and loaded it into the syringe to store it. When mixing with an equal amount of Ecoflex 0035 fast B, it will cure within 10 minutes (Figure 5 a). We purposely chose 4% which is a higher dosage than the amount used for the conductive silicone layer to mitigate local resistance increase issue when connecting with electrodes. Also, after tested 12 samples (3.4cm × 0.8cm × 0.18cm), the instant conductive adhesive shows a conductivity of 0.013 ± 0.002 S/cm. We treat this as an integral part of our contribution to better support users to instantly connect the current system with electrodes. For the conductive electrode choice, we mainly considered the flexibility of materials that can be easily made into desired shapes and is malleable enough not to intervene the deformability of the system. In Figure 5 b-d , we have tested three different types of conductive-fabrics-based connection methods, *Ag conductive hoop-and-loop* and *Zeven+30 conductive copper fabrics* from [66], *Silver-Coated Vectran Thread* from [33]. The first two options are both purchased in sheets and easy to cut into various shapes. Conductive thread can be a replacement for the copper wire which is a common electrode connection method for the electronics system.

4.4 Fabrication Methods

Our goal is to develop accessible fabrication methods to enable non-expert users to explore making various devices using our PITAS system. We considered three factors when choosing and testing the fabrication methods: 1) machine or tool cost; 2) whether the machines are commercially available and can fit into a home environment; 3) the net fabrication time.

4.4.1 Vinyl Cutting and Laser Cutting Based Method. Vinyl cutters support promising outcomes in the DIY community especially considering their low machine cost and the small space required for the machine setup, which serves as a great tool for cutting different thin-sheet materials (*e.g.,* fabrics, paper, cardboard). However, cutting silicone is not common due to the visco-elastic properties of silicone, which make it challenging to cut through the material by a normal cutting blade. Also through the experiments, we observed the scrolling mechanism tend to peel off the silicone sheets from

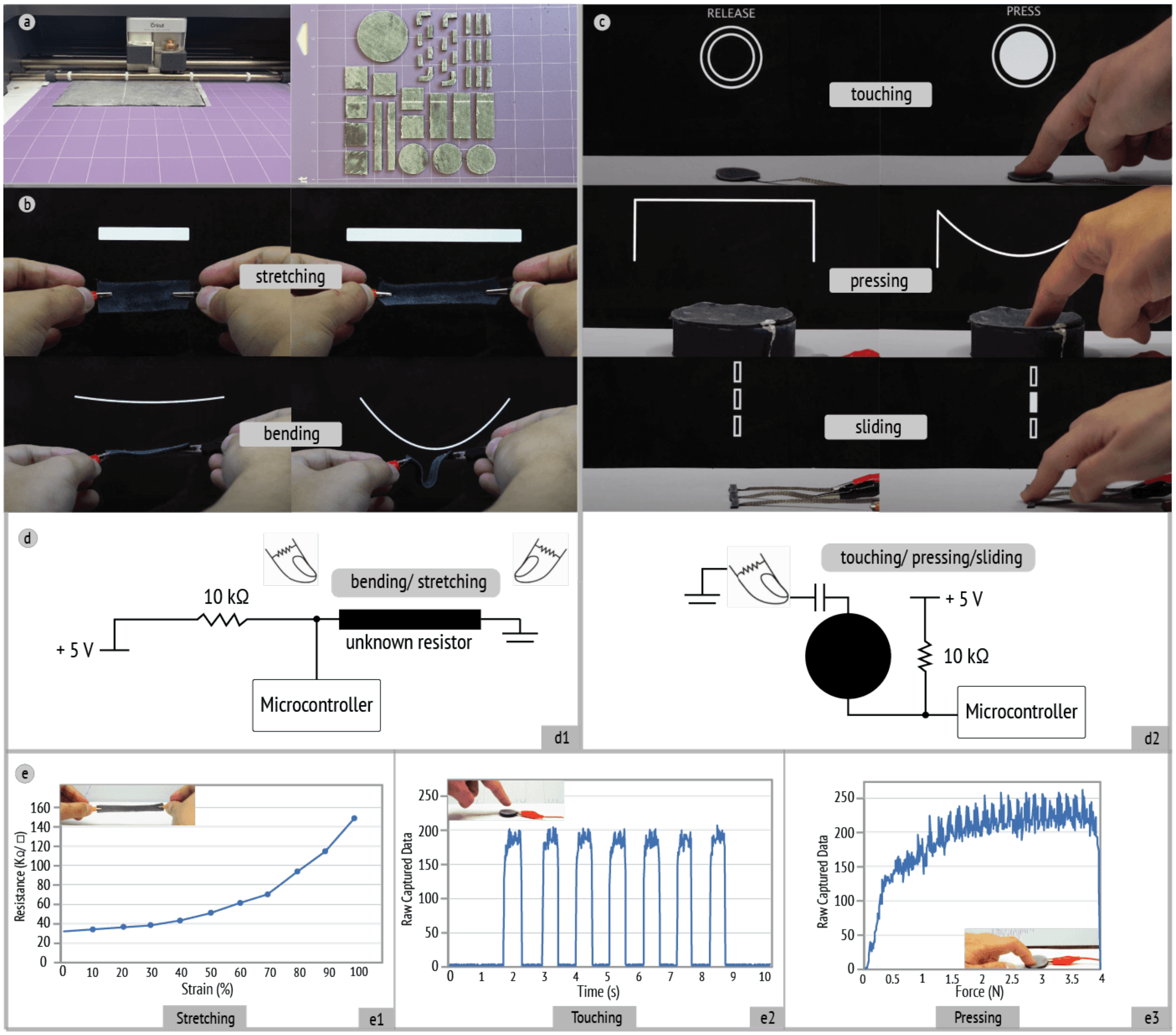

Figure 4: (a) Vinyl cutting process for the sensing samples; (b) Two example resistive sensing modalities: stretching and bending; (c) Three example capacitive sensing modalities: touching, pressing and sliding; (d) schematics for both sensing approaches; (e) Raw sensing data for resistive (stretch) sensing and capacitive (touch, press) sensing.

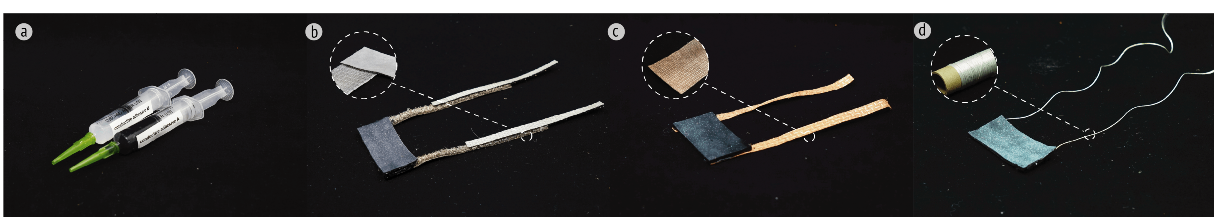

Figure 5: (a) Two parts of the instant conductive adhesive; (b) Conductive hook & loop connection method; (c) Conductive fabrics connection method; (d) Conductive thread connection method.

the cutting board because of silicone's high surface energy which made it difficult to adhere to normal surfaces. To tackle these fabrication issues, we bound the silicone sheet in-between two sheets of parchment paper. We also found a rotary blade can provide much better-cutting results compared to normal cutting blades [9]. With the machine setup, we can consistently cut through up to 3mm

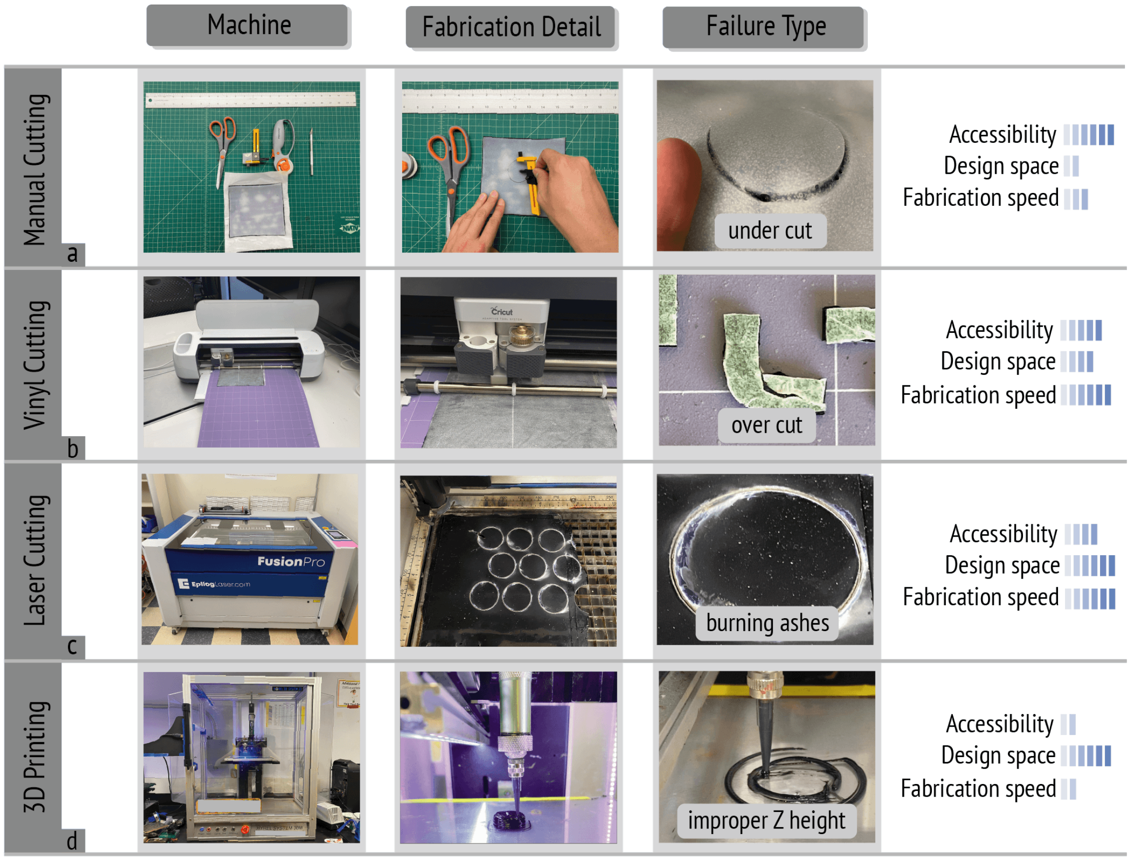

Figure 6: Four different fabrication approaches: (a) manual crafting; (b) vinyl cutting; (c) laser cutting; (d) optional 3D printing.

silicone sheet thickness which typically contains 1mm conductive silicone sheet and 2mm phase transition actuator sheet (shown in Figure 6 b). We also observed the rotary blade will sometimes overcut the sample, so we suggest keeping a 5mm gap in between two adjacent cutting lines.

Laser cutting is another subtractive fabrication method for cutting silicone material into desired shapes which can process a wider range of materials and thicknesses with higher precision. For our experiment, we used an Epilog FusionPro 48 (120 Watt) laser cutter. The cutting power utilized ranged from 20% to 50%, and the speed utilized ranged from 30% to 80%. For different material thicknesses, different combinations of cutting power, speed, and cut passes should be applied, but certain combinations are more preferred than others. For example, for cutting a 4mm sheet (1mm conductive sheet and 3mm phase transition actuator sheet), 50% power, 50% speed for 4 cut passes and 30% power, 65% speed for 5 cut passes can both cut the sheet through. We prefer the lower power settings since our phase transition actuator sheet is heat sensitive. Higher power would risk evaporating the embedded ethanol around the cutting edges of the sample. Also, lower power will generate less cutting ash from the conductive silicone sheet. We also recognize the conductive sheet layer is harder to cut through than the phase transition side, so we recommend cutting this stubborn layer first to avoid overcutting on the phase transition actuator layer.

4.4.2 Manual cutting. Among all cutting methods, manual cutting is the most accessible and rapidly available option. By using simple tools (*e.g.,* rulers, scissors, crafting knives, or even compass circle cutters), one can cut PITAS into desired shapes without the installation and operation of any machines. Besides accessibility, the manual crafting experience is also a good way to let people experience the proposed material system without any further process. This reflects great tinkerability by immediate feedback of materials.

4.4.3 Optional 3D Printing Method. Silicone 3D printing is a widely used fabrication method, but limited resources exist in the consumer market. The printing technique is available but not matured or easily accessible and mostly limited within research labs. Due to its less accessible manner, we include 3D printing as an optional fabrication method. We searched the market and used Hyrel system 30M as our silicone printer. 3D printing PITAS requires printing processes for both the actuating layer and the sensing/heating layer. Because of the high viscosity of the sensing/heating layer, one can directly load the material to the syringe to print. We normally choose to use a 16 gauge syringe tip as our main printing tip, but one can use tips with different diameters for wider or thinner traces. We also recommend using disposable sterile syringes instead of the metal extruder included from Hyrel (*e.g.,* EMO-25 extruder), since the two-part silicone will ultimately cure inside the extruder. For printing the actuating layer, we choose to add 3% silicone thickening agent (THI-VEX, Smooth-On) to part A to thicken the material and make it more printable. For the machine setup, two key factors should be considered: the flow rate multiplier and proper Z height. For example, the conductive silicone material is very viscous and requires a material flow rate multiplier of 5 in the Hyrel system while for printing the actuating layer, a lower flow rate multiplier of 2 can be applied. Proper Z height also plays an important role for achieving good contact between two consecutive layers, and we have used 0.3mm as our main Z height value in the system.

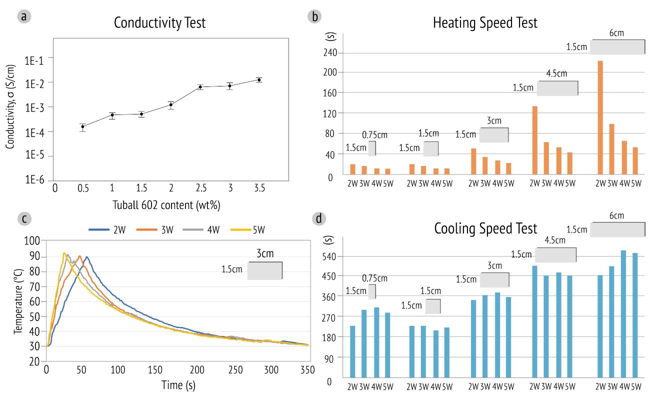

Figure 7: (a) Conductivity test results; (b) Heating speed test for five samples with different sizes; (c) Temperature curve for different input power; (d) Cooling speed test for five samples with different sizes.

5 SYSTEM CHARACTERIZATION

5.1 Electrical Properties For the Conductive Silicone

5.1.1 Conductivity Test. Researchers have tried different ways to make conductive elastomeric materials, including embed graphite powders, carbon nanotubes [44, 71], carbon fibers [74] or liquid metal (EGaIn) [5]. Most of the existing methods require 10%-15% of the filler material to be added to the elastomer matrix, and mostly require complicated mixing steps and operation environment. We chose a graphene nanotube-formulated silicone filler Tuball 602 as our conductive filler for its low dosage requirement, simplicity of the mixing process, and efficient conductivity. Most carbon nanotubes are powders and have safety concerns for inhalation, which may bring them in contact with the cardiovascular system. Tuball 602 contains single-layer rolled-up sheets of graphene that are more than 5 μm in length. Tuball 602, when sold, is already mixed with a matrix material that made the Tuabll 602 a paste instead of powder. Another great advantage is the simple mixing method for Tuball. According to its guideline, one can simply adopt a mechanical stirrer to mix the Tuball filler to the silicone elastomer. Also, Tuball requires very low working dosage from 0.3–5%, and our conductivity test in Figure 7 a has shown the results with different dosages from 0.5-3.5% by mixing the Tuball 602 with Smooth-on 0050. For each dosage, we have tested 10 samples with a dimension of 3.4cm by 0.8cm by 0.18cm each. Conductive epoxy and a small piece of conductive fabrics are attached to both sides of the sample, and two-probe measurement setup is applied. For the conductive silicone layer in the paper, we mainly adopted 2.5-3% as our main recipe. The conductivity can further go down by increasing the dosage to 3.5% or more, but the material cost and the stiffness of conductive silicone material will also go up as a trade-off.

5.1.2 Heating & Cooling Time. PITAS is a heating based system, relying on the heat to penetrate the entire matrix to trigger the phase transition and the overall deformation. So heating process plays an essential role in the actuation process. We have tested five different types of sample with different dimensions from 1.5cm by 0.75cm, 1.5cm by 1.5cm, 1.5cm by 3cm, 1.5cm by 4.5cm and 1.5cm by 6cm (See Figure 7), each sample contains 1mm of phase transition layer and 1mm conductive silicone layer. We evaluated how different heating dimension along with different electrodes distance can affect the heating/cooling rate and how different provided power can affect the heating/cool rate. Figure 7 b & d shows a clear trend for the heating time. When the heating area for the sample is smaller, which at the same time means the distance between two electrodes are closer, the heating time is much faster. Similarly, for a fixed heating dimension, the more power we provide, the faster heating rate we can achieve. Regarding the cooling rate, we can see the cooling difference between different samples, but it's not significant within one sample set when they are heated with different power. Our interpretation is since even the samples are heated with different amount of power, but we stop the heating process and start counting the cooling time when they reach 90°C, so the cooling rate performs similarly for different power. In Figure 7 c, we also provided the entire heating & cooling curve for the sample with dimension of 1.5cm by 3cm and it shows the cooling process takes substantial time. For example, the heating time for the sample at 5W takes around 25 seconds to reach 90°C while the cooling time takes around 330 seconds to cool down back to the room temperature.

5.2 Mechanical Properties For the Phase Transition Actuator

5.2.1 Bending Test. On top of the test that we carried out for the heater, we have also tested how different volumes of the actuator can cause differences in the deformation. Since our focus is on the thin-sheet form factor for the PITAS system, in Figure 8 a and b, we have included testing samples of 1.5cm by 4.5cm dimension with different actuating layer thickness ranging from 1mm to 5mm. Also the samples have a 1mm conductive silicone layer as the heater. As we have observed that 3mm and 4mm samples perform the best results, we speculate when the actuator is getting thicker, it becomes more difficult to uniformly heat up the entire matrix. Another aspect from this actuating results is the heat dissipation time from the conductive silicone heater to the phase transition layer. For example, The full actuation time for the 1mm sample is

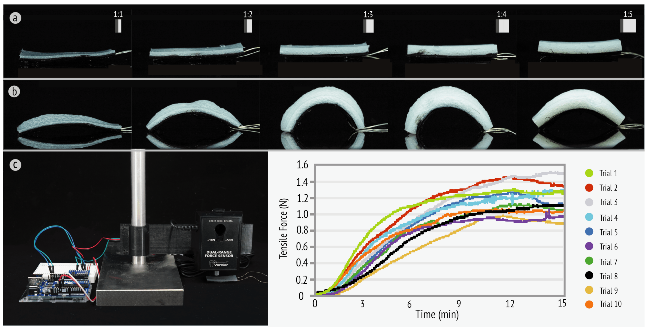

Figure 8: (a) Five phase transition actuator samples with different thickness; (b) Different bending curvatures achieved by the phase transition actuators; (c) The force testing setup and the results for the 3mm phase transition actuator sample.

around 90s, while the 3mm sample will take almost 220s to get fully actuated.

5.2.2 Force Quantification. Ethanol/silicone based phase transition actuating system benefits from its high stress (up to 1.3 MPa) [35], which can play an important role when fabricating tactile devices to deliver information. However, we would like to note that since we keep a thin sheet form factor, it would not achieve the stress level reported in the previous paper [35]. Nevertheless, the phase transition actuator system is relying on the vapor pressure generated by the ethanol to deliver force, so one can stack up multiple layers of the material in order to achieve bigger force, but will inevitably lose the benefit of PITAS's thin form factor. We have carried out the force testing for PITAS with a sample dimension of 1.5cm by 4.5cm, and we adopted 3mm thickness from the bending test results. The setup for the testing is shown in Figure 8 c. We put the PITAS sample beneath the force gauge, and consistently apply 3W to heat up the samples and we achieved the force curve on the right side of Figure 8 c. The maximum force detected by the force gauge is around 1.5N for our sample. We have repeated this test for 10 times and achieved an average maximum force of 1.2N with a standard deviation of 0.2N.

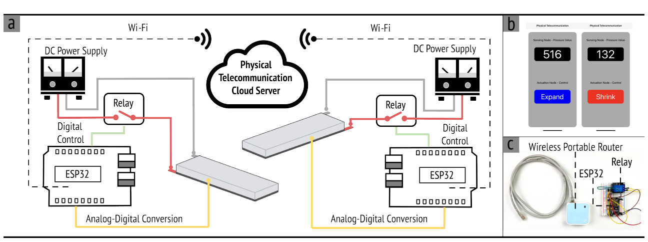

Figure 9: (a) Configuration of hardware system; (b) A mobile application to visualize the sensing data; (c) Actual devices that participants used in the workshops.

6 COMMUNICATION & CONTROL METHODS

Our hardware system consists of two core parts: (1) a device that can measure the conductivity, actuate phase transition, and communicate to other devices over the Internet, and (2) a cloud server that receives, stores, and retrieves the sensing data. Although the proposed system is currently based on an ESP32 module, our approach can be easily adapted to other embedded platforms (Figure 9).

Device: We used ESP32, a widely-used, off-the-shelf, and open-source hardware platform [12]. When a participant connects a phase transition module, the device measures its conductivity 20 times using the analog-to-digital conversion function in ESP32 and averages the values to determine the baseline of the module. This initial calibration is required since the conductivity of each module may vary due to its shape, size, and thickness. After that, the participant can press the surface of the phase transition module to actuate the phase transition in another device. Though we simply detected the resistive or capacitive change, the sensing materials used in this study has a great potential to recognize various gestures and motions through simple machine learning and signal processing techniques [58]. For actuation, we connect the power source using an on/off relay switch. Note that the voltage value in this study is relatively high (*e.g.,* 50V), but the required current is relatively low (*e.g.,* 60mA). Therefore, a battery-powered actuation can be developed in the future using DC-DC voltage converters. All data communication was done through Wi-Fi.

Cloud Server: We developed the server part using a RESTFul API based on Spring Framework [22]. This part allows a device to communicate with other devices anywhere with the Internet connection. For the sake of experimentation, we paired two devices. At first, a device sends its node identification number and sensing information to the server. Then the server transmits the data to another mapped device to change the phase of the device. Since our communication system is in the form of a star topology, system designers can easily modify the communication architecture to 1-1, 1-N, or N-N formats in the future.

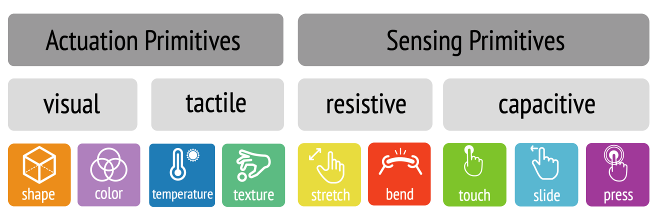

Figure 10: Overview of the actuation and sensing modules for PITAS.

7 APPLICATION

We showcase two application examples that highlight the potential use cases of PITAS, and each application artifact exemplifies different actuation and sensing methods for PITAS (Figure 10).

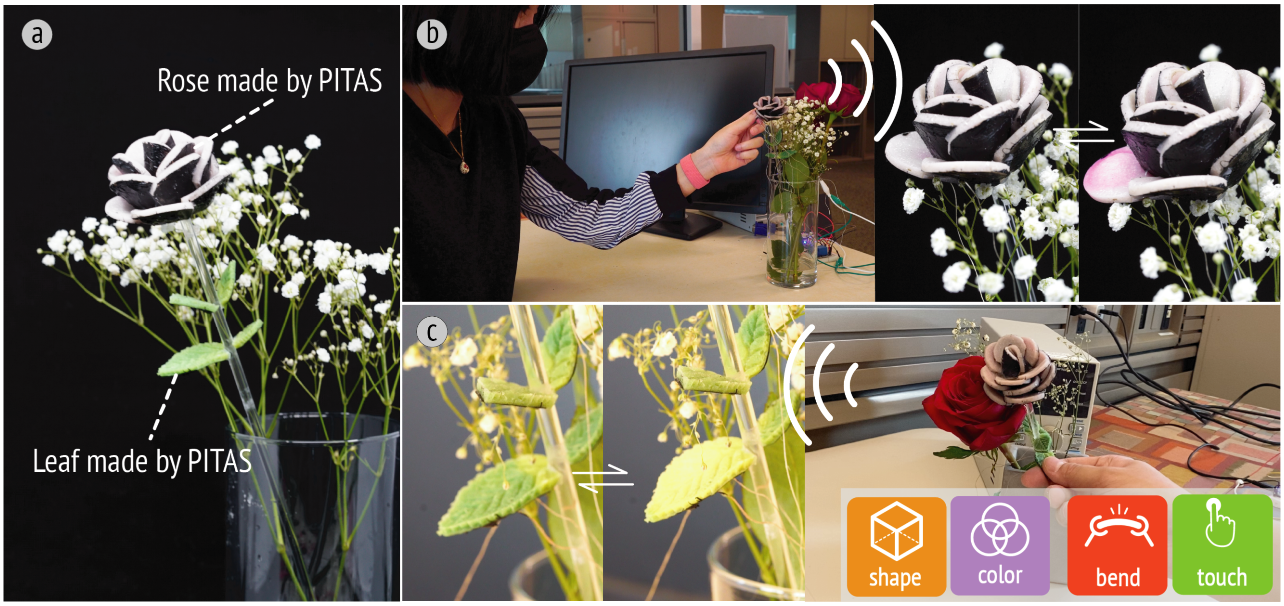

Figure 11: (a) Overview of the artificial rose and leaves fabricated by PITAS; (b) Delivering color change (colorless to pink) and flower blossom to partners remotely when missing each other; (c) Delivering the depression by enabling the color change (green to yellow) and leaf hanging down remotely.

7.1 Home decor artifact for emotional communication: 3D artificial rose

Inspired by the aesthetic demonstration from *Thermorph* [4], we developed an artificial rose whose petals and leaves are made of 3mm by 1mm PITAS sheet with embedded thermochromic pigments. Usually, thermochromic pigments are added to Ecoflex 0050A after it is mixed with ethanol with a weight ratio of 1 to 80, then we let it mix with Ecoflex 0050 B to make the PITAS sheet. For this application, we laser cut the flat PITAS sheets with 2D rose petal patterns and then manually fold and glue the pedals into 3D rose. When touching or bending the petals or leaves, people can remotely deliver the emotions of missing each other (with petals blossoming and color turning into pink from colorless, Figure 11 b) or share melancholy or loneliness (with leaves hanging down and turning to yellow from green, Figure 11 c). This application is intended to evoke an emotional interaction enabled by the adaptability and deform-ability of PITAS that can be endowed with thermochromic functionality and rolled up into desired 3D shapes.

7.2 Office accessory for information delivery: Actuatable sticky notes

One key feature of PITAS is how easy and accessible it is for novice users. They can customize it into desired shapes to actuate daily objects by simply using scissors or a craft knife to cut. We demonstrate this by using a pair of scissors to manually cut a PITAS sheet into different shapes and place them onto Post-it notes with different arrangements to remotely synchronize different stages of a task shown in Figure 12 a. Users are able to remotely update the status of their work and communicate it to his/her team. This is done with a cut-and-attach approach in which modules are fabricated by hand without involving additional fabrication machines, shown in Figure 12 b. In this example, a long strip of PITAS placed in the middle of a Post-it note causes a bigger curl in the middle. A strip placed diagonally causes a side flip of the Post-it note, while two short strips cause a wider but smaller curl. These can represent an accomplished, stuck, or in-progress task respectively.

8 WORKSHOP

PITAS can deliver physical information beyond local spaces, so in order to extend the application examples, focusing particularly on physical telecommunication, we conducted a workshop to gauge the usability of PITAS techniques for non-expert makers and investigate the design space for physical telecommunication scenarios. After obtaining university IRB approval, we recruited 13 participants by snowball sampling (Female=6, Male=7, Aged from 21 to 29). Among all the participants, 8 were from engineering background, and the other 5 participants were from design background. Most of the participants have experience with prototyping interactive systems except for three. Also, 12 participants reported that have never observed or used any types of physical telecommunication devices in real life and none of the participants have used phase transition actuators before.

8.1 Workshop Agenda

We carried out two sessions in a studio-like lab space (shown in Figure 13 a). For the first workshop session (3-hour group activity), we aim to enrich the participants with the understanding of physical telecommunication/PITAS technique and also initiate design ideation. This session consists of four stages: 1) 30 mins introduction about physical telecommunication; 2) 30 mins for existing soft

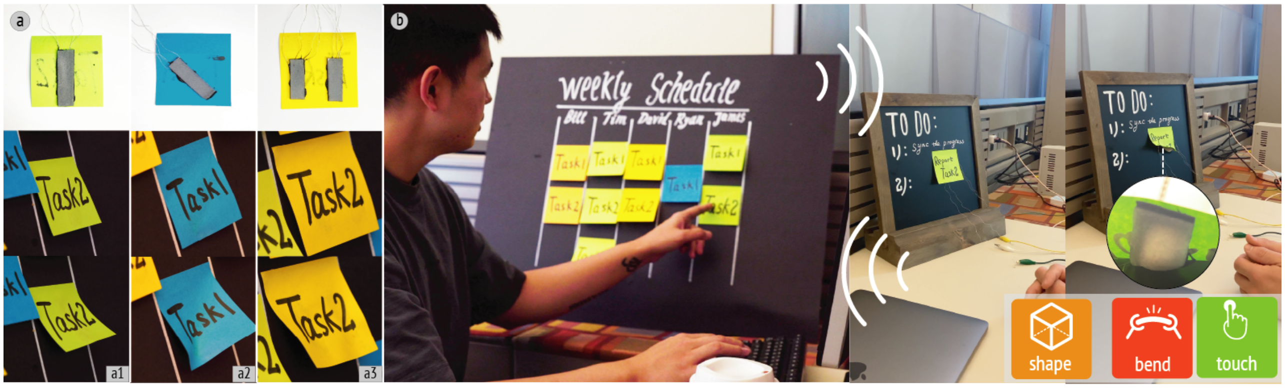

Figure 12: (a) Different actuation modalities; (b) Remotely synchronize the task progress by tapping or bending the Post-it note with PITAS attached on the back.

actuators and sensors; 3) step by step mechanisms and fabrication methods for PITAS; and 4) card sorting activities for 1 hour [59]. For the card sorting, participants are divided into four groups to play with different cards: 1) input modules (*e.g.,* slide, touch, pressure); 2) output modules (*e.g.,* expansion, twisting, bending, color-change); 3) location (where exactly they will place the modules, *e.g.,* wrist, finger, windowsill); 4) environment (*e.g.,* office, school, home). We asked participants to pick one or two cards for each category and have a team discussion for applying them to physical telecommunication scenarios. The results are summarized in Figure 13 b.

We continued the workshop as a full day (7 hours) hands-on studio activity to prototype design applications they envisioned. The second session is divided into three stages: 1) making single PITAS module as a warm-up activity for 1 hour; 2) making proposed physical telecommunication scenario for 5 hours; 3) post-workshop survey and discussion for 1 hour. The main goal of the workshop is centered on validating the usability of the proposed PITAS techniques and the potential design spaces using PITAS for physical telecommunication scenarios.

8.2 Results

Four teams have finished the fabrication and carried out physical telecommunication scenarios by placing the paired modules on each side of the room (approximately 3-5 meters distance). We have summarised the results for the four scenarios in Figure 14 b1, b2, b3, b4. Details are as follows: 1) Group1: a pair of wrist bands for lovers, shown in Figure 14 b3. When one person misses the other one, they can touch the modules on their wrist to convey the feeling of missing each other. 2) Group2: personal status notification device to notify the personal status between two parties remotely, and the results are summarized in Figure 14 b4. One can press the PITAS module attached by the inner side of the door to lift up a notification board to inform the people inside the room. 3) Group3: Remote pets food dispenser controller that allows the pets to remotely notify his owner (shown in Figure 14 b2), which meanwhile enabling the owner to remotely actuate the food dispenser to feed the dog. 4) Group4: nurse & patient notification modules within a hospital environment, shown in Figure 14 b1. Patients can remotely convey physical messages to the nurse about his physical conditions.

8.3 Findings, Limitations and Design Space

8.3.1 Choosing manual cutting over other fabrication methods. We introduced three available fabrication methods including two digital ones (vinyl cut and laser cut) and manual cut. All participants, to some degree, used manual cutting throughout the workshop. Many participants mentioned that applying only manual cuts can enable sufficient quality of the fabrication results and is the most time-saving and easiest fabrication method among the three. Participants also discussed the craft-friendly aspect of the PITAS sheet. For instance, P7 noted, "*because the material is soft and thin, made it easy to cut, so I prefer to use scissors (instead of using digital fabrication machines).* (P7)" This is an interesting finding that echos the design intention of making PITAS in a thin-sheet form factor. Some of the participants pointed out the importance of manual craft accessibility by making a contrast to the optional 3D printing method. P4 and P12 commented that 3D printing requires not only hardware knowledge of using 3D printers, but also relevant design skills such as 3D modeling. All other participants also agreed that layering up 2D sheets into a 3D structure should be more useful and engaging for most makers unless they want a more precise 3D geometric design.

8.3.2 Usability of PITAS techniques. The proposed pipeline can be divided into 5 stages: 1) cutting the pieces into desired shapes; 2) preparing the electrodes; 3) gluing the electrodes; 4) assembling the pieces; 5) connecting the assembled module to the hardware. At the beginning of the second session, we asked all participants to follow a simple task by fabricating a single module. All participants successfully finished the given task and demonstrated actuating their modules with the power supply (shown in Figure 14 a4). Throughout this warm-up activity, several participants (p2, p4, p6) commented that gluing the electrodes to the sheets is challenging as they don't know how long it will take to dry the conductive adhesives. P7 mentioned that a conductive adhesive similar to copper tape that can be easily adhered to PITAS would be highly useful if available in the near future.

8.3.3 Design editor and electrodes placement. Based on our observations and the feedback from the participants, the electrodes connection so far is the most complicated step. Participants all agree that the current instant conductive silicone adhesive and

Figure 13: (a) Workshop activity overview; (b) Card sorting activity: Finalize the physical telecommunication scenarios that participants will make.

the conductive thread already eased the electrode connection step, especially comparing to jumper wires/alligator clips, which are not suitable for being directly connected to the soft silicone system, but a more peel-and-stick option could further lower the challenges for the connection. Additionally, a visualizer to assist users to know where to place the electrodes and the resulting deformation for PITAS system is necessary. P7 noted: "*Figuring out where to place the electrodes is difficult and it's hard to imagine where it would bend when the geometry is complicated*". We believe the editor should contain two features: First, it should enable the users to place the electrodes on different areas of PITAS; Secondly, the visualizer should allow users to visualize the deformation when having different PITAS geometries, combing with different material extensions or applied with different power.

8.3.4 PITAS's design insights. Participants tend to choose the visual information (shape change and color change) over tactile information (tactile add-ons and temperature change), and only group 4 adapted the tactile property to pinch the inner side of the nurse's wrist. None of the outcomes used temperature change.

According to the post-survey, ten participants rated color change and shape change to be more inspiring and useful than tactile add-ons and temperature change because "*color and geometry change are more obvious and also more powerful for communication.* (P7)" Three other participants preferred temperature change because "*The color change is very obvious, however, the temperature (change) has more potentials to be used broadly (on body) especially with skin touch.* (P11)", which also brings an interesting point that different behavior of PITAS might fit different scenarios. For example, visual information is better suited for in-the-environment telecommunication scenarios, while temperature and tactile information are

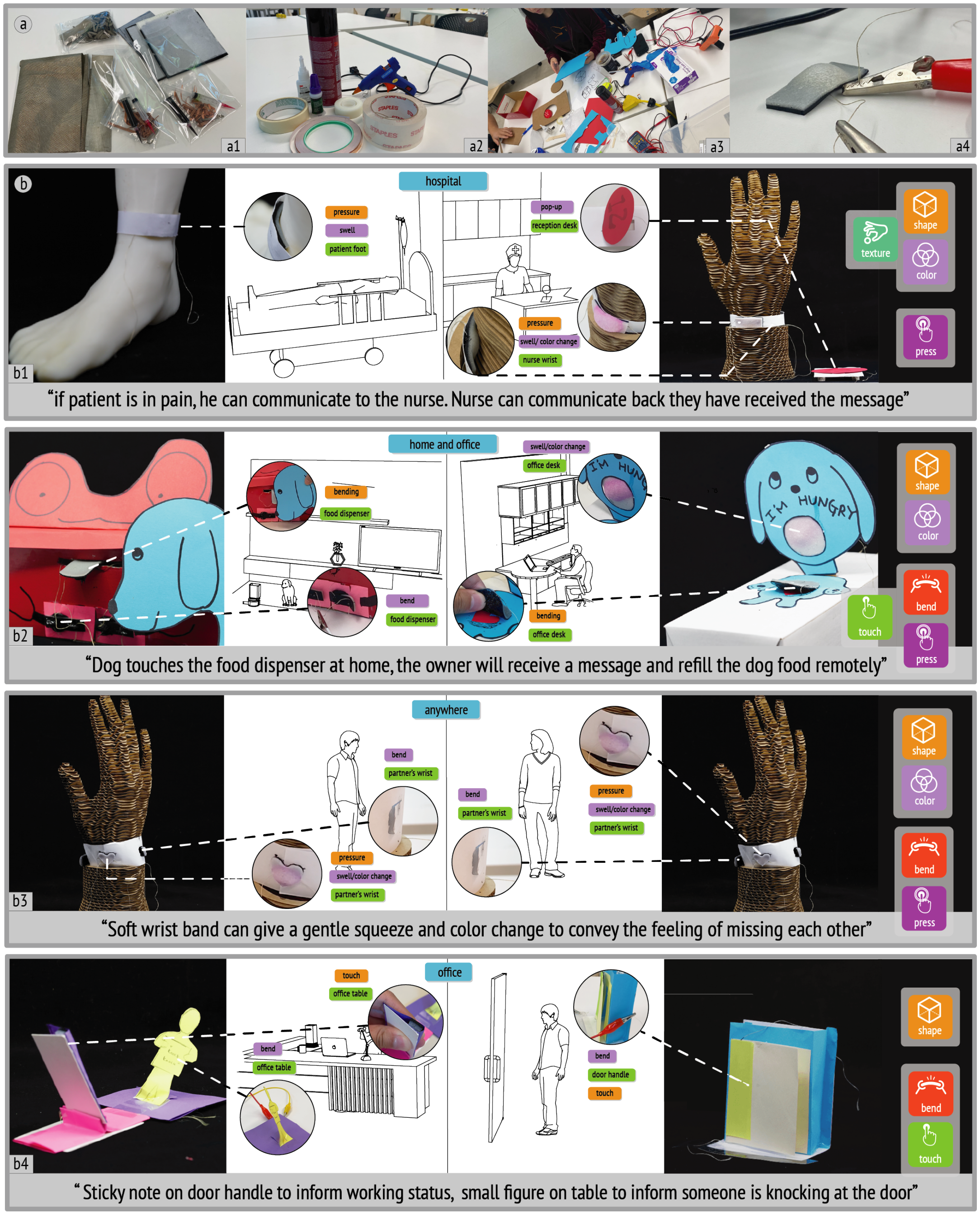

Figure 14: (a) Workshop activity 2 overview; a1-a2: Material given to the participants; a3: Fabrication progress overview; a4: Single module fabrication task; (b) Proposed physical telecommunication scenario fabrication results.

more for on-body interfaces. During the post-discussion, participants also mentioned the exciting potential of making custom PITAS sheets, given the simplicity of the PITAS sheet fabrication process, by adding additional materials to PITAS (*e.g., magnetic powder, electroluminescent pigments*) to enable versatile features to enrich different types of physical telecommunication scenarios.

9 LIMITATION & FUTURE WORK

In addition to the insights that we gained from running the workshop, we have also observed certain weaknesses that PITAS can improve in the future:

Material Preparation As previously mentioned, the current version of PITAS is prepared by the researchers. Even the mixing steps for both the phase transition layer and the conductive silicone layer are not complicated – only requiring simple mixing stirrers, these pre-process steps are still constraining PITAS from being adopted by a broader spectrum of users. Also, the current PITAS sheets are mostly molded, which does not always provide consistent layer thickness. We believe a film applicator can be a good candidate to make the PITAS with more uniform thickness like the one has been used from *Silicon Device* [40]. We also envision that PITAS or a similar type of actuating and sensing embedded materials can be commercially available for direct purchase in the near future.

Driving Voltage Even compared with some other types of soft material systems (*e.g.,* electroactive polymers), which usually require over 1kv or more to drive the deformation, PITAS demands low voltage. However, the voltage requirement (*e.g.,* for a 1.5cm by 4.5cm sample) is still usually around 50V, 60mA which is a limiting factor and further constraints the practical usage of PITAS. This can be tackled by further adding higher dosage of conductive materials to reduce the resistance of the conductive silicone layer, but inevitably can sacrifice the softness of the system. Also, this high voltage requirement makes direct touch to the conductive silicone layer very dangerous, especially for any potential on-body applications. A thin silicone coating which can act as the dielectric/protection layer should be applied if users will be in contact to the conductive silicone side.

Actuation Speed PITAS mainly aims at showing the possibilities for DIY different types of physical telecommunication modules with taking the material advantages by providing large strain, high adaptability to different inclusions or sensing/actuating embedded. However, the current mechanism has been limited by its actuation speed. The current full actuation time is in the order of minutes. To speed up the actuation cycle, mixing the conductive material, ethanol, and the silicone matrix all together will help with the heat distribution throughout the system much better, and that would be the next step for us to investigate.

Material Preparation and Use Safety The material preparation steps for the conductive sheets and the instant conductive glue of PITAS involve the manipulation of Tuball 602, containing single-wall carbon nanotubes which is traditionally categorized into carcinogenic materials that can damage the cardiovascular system [44]. Even for Tuball 602 matrix, the carbon nanotubes are already encapsulated within a resin carrier instead of free powders to reduce its airborne exposure potential. However, when preparing the sheets or processing the fabrication (*e.g.,* laser cutting, hand cutting), one should complete the necessary safe handling procedures and wear proper personal protective equipment (protective gloves, goggles, masks) and must be under a good ventilation environment (*e.g.,* fume hood). We list the official material process document from Tuball here (Safe Handling and Use of Tuball Guideline).

10 CONCLUSION

We presented PITAS as an example leveraging the capability of personalization of soft robotic material. We outlined three highly accessible cutting-based fabrication methods (*e.g.,* manual cut, vinyl cut and laser cut) as well as an optional 3D printing method. Our PITAS techniques have demonstrated that it can enable four types of different physical elements, including shape, color, texture, and temperature changes. We also reported a user study with 13 non-expert makers to validate the usability and design space of the proposed method. The study results along with our additional application examples indicate that PITAS can stretch the bounds of personal fabrication for soft materials and enable more actuating and sensing, integrated modalities. While our focus is on proposing accessible fabrication methods in this paper, we envision that PITAS techniques could be far more expanded through emerging reliable liquid 3D printers that are increasingly entering the market.

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