ABSTRACT

XIE ZIYANG. Silver Nanowire-based Heater: It's Fabrication and Applications in Self-folding Structure and Wearables. (Under the direction of Dr. Yong Zhu).

The focus of this study is fabricating and controlling a flexible, highly conductive heater. And two applications of this heater are studied. One is to trigger the folding of pre-strained shape memory polymer and realize a controlled sequential folding process. Another is to create a wearable heater which shows its potential in medical uses and textiles.

In the folding design, material, heating control is introduced and compared. Taking heating power as control object, folding angle vs heating time experiments are done under different input power. In the meantime, FEA analysis is done to analyze the heat flow of this process. Simulation results are consistent with the experiment, there's a clear relationship between heating power and folding angular speed.

In the wearable heater temperature control part, measuring and output circuit and designed for controlling the heater's temperature. Harnessing the temperature coefficient of resistance (TCR), we can measure heater's temperature by measuring the resistance of the heater. LABVIEW in PC is used for controlling and calculating support. The collected voltage signal is transferred to output control signal through a PID controller. Temperature range can be precisely controlled within ±0.5℃. And response time is about 0.13s which is good enough for a heater.

Silver Nanowire-based Heater: It’s Fabrication and Applications in Self-folding Structure and Wearables.

by
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DEDICATION

To my parents, Hongmei Yang and Ming Xie

BIOGRAPHY

Ziyang Xie received his B.S degree in Vehicle Engineering in Xi’an Jiaotong University, Shaanxi, China in 2017. As a thesis-track master student, he joined Dr.Zhu’s group (Nanomechanics and Nanoengineering Laboratory) in October, 2018. His interests root in Micro/Nano scale mechanics and control theory.

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CHAPTER I

Introduction

1.1 Shape transformation

Shape transformation plays an essential role in both artificial tools and natural livings. From folding and recovering of satellite solar panels, which is in very large scale, to micro-scale self-assembly structures [1], shape transformation technique greatly benefits people. In the nature, Flower blooming and animal's movement (muscle contraction) largely depend on shape transformation. Next, we are going to look into the details of shape transformation and its function in different fields.

1.1.1 Shape transformation in nature

Many kinds of nature livings including marine and land creatures harness shape transformation as their major tool to make transformation. Different creatures show various way to move and eat. Caterpillar, which is a small insect exist in every part of the world, is a perfect example of using various shape transformation method to make locomotion. Caterpillars can do inching, crawling as well as rolling[2] by controlling its body's bending angle and bodyparts like claws attaching to the ground. This locomotion method inspires researcher to create some bio-inspired soft robot. In different environment, different moving strategy is applied. For rolling is the fastest but uncontrollable locomotion, when caterpillars meet danger, rolling is the best way to escape. Soft robots[3] already developed a rolling as a very fast method for locomotion. Apart from caterpillar, some marine animals like jellyfish, also make special shape transformation. By shrinking its bodyparts, serving as jet and paddle[4], octopus can swim in high speed in water.

Instead of making locomotion, shape transformation allows animal hunt, gather food and other activity. For example, elephants bend their trunk to grab food and octopus hunt by curving their tentacle food. Some plants also use shape transformation to achieve certain target. Flowers bloom to deliver their pollen. Sun flowers bend their stems for more sunlight. Vine plants use their tendril to climb up trees and walls.

Along billions of years' evolution, shape transformation mechanism is widely used in every single living creature. Shape transformation exists in soft materials, like muscle and fat. Compared with rigid one, soft structure shows its advantage in more freedoms and less requirement for accurate movement. Nowadays researchers are inspired by these living creatures and created many bio-inspired soft robotics. Different from conventional robots which are rigid and require a very high precision in sensors and actuators. Soft robot can survive in harsh environment and survive after strong hit.

1.1.2 Shape transformation in robots and artificial systems.

Mimicking human's body structure, human-like robots are invented with many components, including rotational and linear joints, sensors, and actuators. Every joint makes shape transformation (rotates or linear move) under the control signal. However, there's still a long way to go before robot can work like human. Different environment will show influence on the robots, for instance, wet road has smaller friction, robot may slip if it failed to adjust parameters. These variables create much more complicated problems as there're many unpredictable situations. Soft robots, however, do not have very high accuracy requirements, and are less expensive to fabricate, will be a potential solution to some easy problems. Inspired with soft-body creatures like caterpillar [3, 5] and octopus, people are looking into soft materials which does not require accurate sensors. Go Q bot, [3]for example, can mimic inching and crawling of caterpillars. And octopus [6] inspired robot and worm-like robot play the major role in soft robotics.

Shape memory alloy [7] shows its advantage in thin film due to its large surface to volume ratio. The most well-known shape memory alloy application is its use for solar paddle [8]. It is a light weight material with high shape memory accuracy in aerospace filed. But there's still some limitations in shape memory alloy like slow deactivation time[9], structural and functional fatigue, and unintended actuation.

Shape memory polymer(SMP) shows its advantage of its low-cost and high chemical [10] stability and is used in many different fields including biomedical device[11], 3D electronics [12], textiles and robot[13]. Pre-strained polymer will shrink when heated above glass transition temperature, and varying strain can be generated by unsymmetrical heating[14]. Different from shape memory alloy, unsymmetrical heating of SMP is able to induce bending angle between 0° to 180°, and this process is irreversible. It's an origami like folding process. Although origami is first used for artwork, its folding process are largely studied by scientist. It is a new potential fabrication technique complementary to adhesive manufacturing, subtractive manufacturing. Origami is a new method for 2D-to-3D transformation and is already applied for fabricating robot [13]. There're ways to use origami to fold 2D-3D structures. In the first method, 2D sheet is first modified with creases in specific area and apply shrinkable polymer as a compressive stress from outside. This stress will trigger buckling of 2D sheet because the stiffness of creases is much smaller at creases. Different 3D structures can be designed and controlled through designing of creases pattern and the strain of shrinkable polymer. The second method is to apply unsymmetrical strain. If the shrinkable polymer is partially heated on one side, there will be a temperature gradient which will induce an unsymmetrical strain in the thickness direction. And unsymmetrical strain will cause the polymer to fold. This method requires thermal controlling, because temperature below class transition temperature cannot generate strain in shrinkable polymer and if temperature is too high, heating area will become unstable.

1.2 Localized heating process

The need for localized heating grows as people are trying to apply more control on heat-induced fabrication process. Time controlled sequential folding [15], for example, controls heating area with time. There’re ways to realize localized heating. Light heating [15] shows its advantage in its controllability of heating area and there’s no wire or battery needed during heating process. Also, different color shows different efficiency in absorbing energy in lights, this help scientist to apply more control on heating process. However, this methods limitation exists in its efficiency and heating speed. As only a small area of printed area absorbs lights energy, it is inefficient way to do batch fabrication. Also, heating power in reported researches is relatively low ($<0.5W/cm^2$)

Compared with light heating, electrical heater is much more powerful, and it is more temperature controllable. By controlling input voltage[16], output power can be easily controlled in real time. Traditional heating wire meets problem in small scale origami application. It is hard to stably attach wires on polymer, and heat convection will be partially block by glue or tape. Also, some origami inspired folding process need control the width of heater[14], and metallic heater is inconvenient to keep its shape when outer strain is applied.

Metallic Nano-wire and Nano-particles, rise as their advanced fabrication process, have been studied for heater use. Together with substrates like polymers[17], metallic Nano-wire and Nano-particles are ideal for fabricating heater. Also, Nanowire could be used for sensors or self-heated textiles[18] since its resistance change linearly with temperature and give clear response to outer strain.

1.3 Metallic Nanomaterials and substrate for heater

1.3.1 Silver Nanowire and its fabrication

Researchers are paying more attention to metallic Nano materials as they are very suitable to be used for heating and sensing material. There are two forms of metallic Nano material: Nanoparticles (NP) and Nanowires (NW). Compared with NP, NW has higher aspect ratio, and this will help NW more likely to survive under large deformation. Silver Nanowire (AgNW) is the most conductive NW. Its application exists not only in heaters, but also in sensors,[18] transparent electrode[19], and shows very good performance electrically.

There're various ways for chemical synthesis of AgNWs: hydrothermal method[20], microwave-assisted process[21] electrochemical technique and template technique[22]. Polyol synthesis process is the most attractive method in this study since it is quick, low cost and easy to mass production. AgNWs produced by polyol process shows 1-40μm long and 30-200 nm wide. Typically, AgNWs with a longer length and larger diameter are more conductive than shorter ones.

In this study, we choose AgNW as the conductive material and fabricate heaters using AgNW with shape memory polymer (SMP), to fabricate a flexible and highly conductive heater. Following Polyol process, mass fabrication is used to support the needs of heater.

1.3.2 Substrate polymer selection

A mechanically and chemically stable polymer should be chosen as substrate. Polydimethylsiloxane (PDMS), a widely used substrate for Nanometallic materials, shows its advantage in low-cost, good bio-compatibility and deformability. PDMS has been used as substrate for sensors [17], transparent electrode [22][23] and wearable sensors. However, due to its low stiffness, PDMS is likely to induce a large strain under outer stress. As substrate for heater, chosen material should not only be chemically stable under relatively high temperature but also mechanically stable to avoid partial strain which will cause resistance change. A partial resistance change in heater will cause overheat on some point and finally cause heater fail. Thus, PDMS is not an ideal substrate for heater use. Polyimide (PI), instead, is an ideal material for heater substrate. It has a high glass transition temperature (400℃), high toughness, smaller thickness and good arc resistance. These properties guarantee heater will work stably under relatively high voltage.

CHAPTER II

Heater fabrication and thermal control

2.1 Heater fabrication

2.1.1 AgNW fabrication and coating

In this research, we use polyol process to fabricate AgNW[20]. The length of the fabricated Nanowire is 30μm to 60 μm. AgNWs are mixed in ethanol solvent and spray coated on the surface of glass palate. Concentration of AgNW should be controlled within 1g/ml to avoid blocking of nozzle which will largely decrease the coating efficiency. Process of spray coating should be slow and at constant moving speed to improve the uniformity of coated AgNWs. After spray coating, AgNWs is attached on the surface of glass plate.

2.1.2 Annealing

After coating, the AgNW is randomly distributed on the glass surface. There're crossings and overlapping of Nanowires among the heater. This is not desired as a heater used for folding. Average attach area would change when the heater is deformed, which will cause resistance change and sometimes failure of the heater. Annealing is needed to stabilize the performance of fabricated heater. Based on the performance of siver-Nanowire[24], 200℃ annealing reduces AgNW's resistance and stabilize its structure. If temperature is higher, AgNW will deform to drop-like Ag particles. Figure 2.1 shows the SEM image of before/after annealing of AgNW. The randomly overlapping of AgNW deform to a node, and the node is more stable conductor and shows lower resistance. As the heater is designed to be flexible, annealing is essential to maintain its function. Change of overlapping/crossing will bring problems in its temperature measuring.

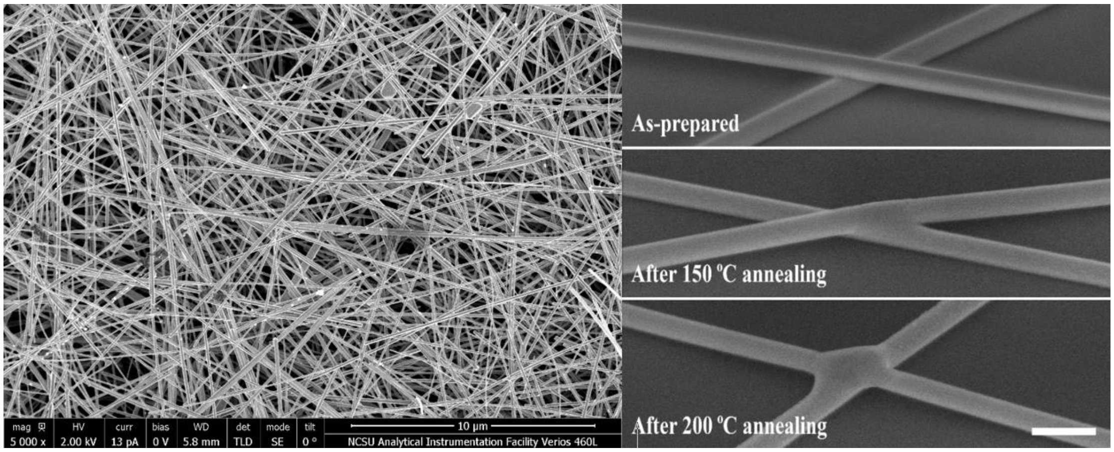

Figure2.1 (a) AgNW image pictured under SEM. (b) After annealing, the cross of AgNW in as-prepared image form a clot. Which will increase the resistance stability and decrease total resistance.

2.1.3 AgNW embedding and wire connecting

In the next step Polyimide (PI) is spin coated on glass plate. (Spin coating speed 500r/min for 30s 3 times). Then PI solution with AgNW is put on hot plate (150°C for 1 hour). After heating, solvent will be vaporized. AgNW on the glass surface will be embedded in the PI. After embedding, heater is conductive on the AgNW embedded side and insulate on the other side. It shows good conductivity and flexibility. In the next step, Laser cutter (VLS6.60, Universal Laser Systems) cut the prepared heater into designed patterns. The parameters are 0.8% power and 50% cutting speed, 1000 PPI in Raster mode. After cutting, Ag/PI film can be removed by soaking it into DI water.

There're two methods to connect the patterned heater with copper wires: Liquid metal and silver epoxy. Both are highly conductive, but liquid metal is more suitable for one-time use. It is hard to move the heater with liquid metal on it. Silver epoxy can fix the copper wire on the heater and will not detach from the surface when it is washed or deformed. This property is desired in reusable heater design thus silver epoxy is selected for wire connection.

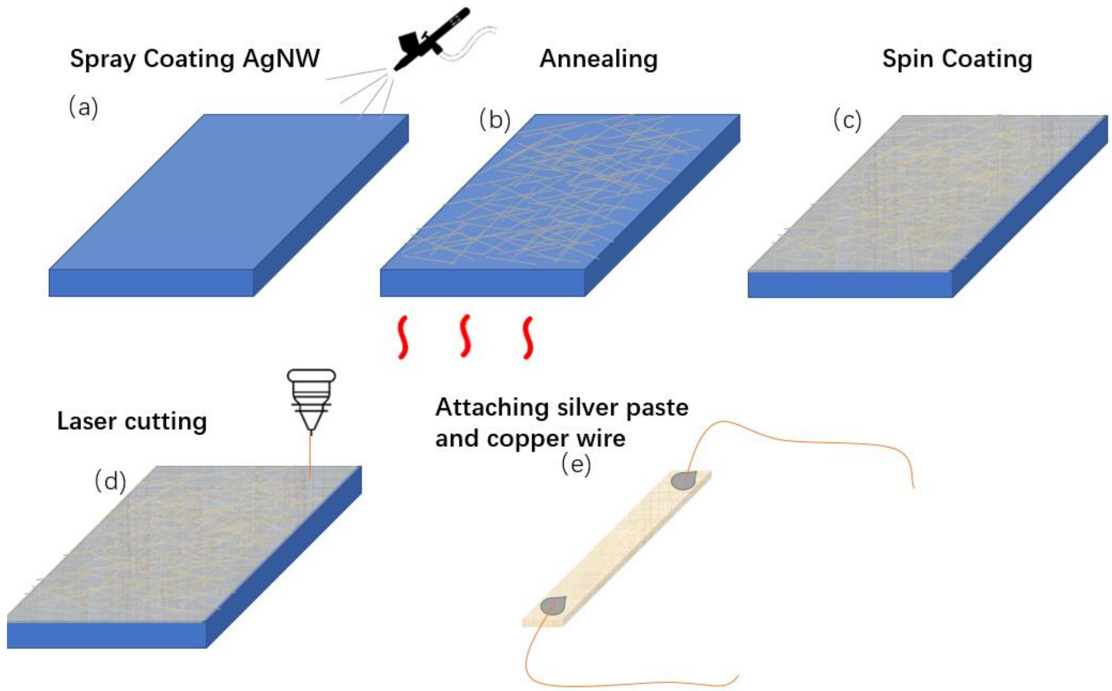

Figure 2.2 (a)AgNW is spray coated on a glass plate (b) Coated glass plate is annealed on hot plate (200℃) (c) PI is spin coated on the glass plate (AgNW half embedded) (d) Heater is laser patterned by using laser cutter. (e) Using silver epoxy and copper wire to connect heater with power supply.

2.2 Heater's thermal control

Thermal control of heater is important as SMP's folding behavior is highly sensitive to its temperature. There're two ways to control the temperature of heater: 1. Plot power-temperature and control temperature by controlling output power. 2. Use thermal camera as temperature measurement and control power supply output.

As to method #1, this is the simplest way to control temperature within certain range. #1 does not require any auxiliary equipment or software, but it's a relatively inaccurate way of control. There's no feedback, it is more likely to cause overheat. So, before the experiment, we need to calculate needed power of certain heater, and set the power slightly below the required temperature. Then increase the voltage step by step until folding begins.

Method #2 shows its advantage in real-time temperature measurement with temperature distribution (caused by ununiform resistance distribution). This method is very helpful for heater testing. But it also has certain limitations. Thermal camera is sensitive to object's surface thermal radiation, and cannot penetrate opaque layer, which makes this method impractical in folding process. Folded layer will block thermal camera thus this method cannot work for the whole process. But this method is good for calibrating input power-temperature curve, as thermal camera is able to measure real-time temperature change.

Environmental setup:

Figure 2.3 shows the testing stage setup, to reduce thermal conduction from heater to environment, heater is attached on PI which is suspended in the air. Thermal camera is used to measure surface temperature of heater. Based on Power supply Agilent 6613C DC power supply, heating Voltage and Current can be controlled. Heating power is calculated by multiplying heating voltage and current. Tested heaters are patterned by laser cutter as 2mm*20mm. The needed heating power is determined by the area of the heater and the required temperature. For folding needs, the working temperature is between 110℃ to 130℃, and the tested range is from room temperature to 140℃.

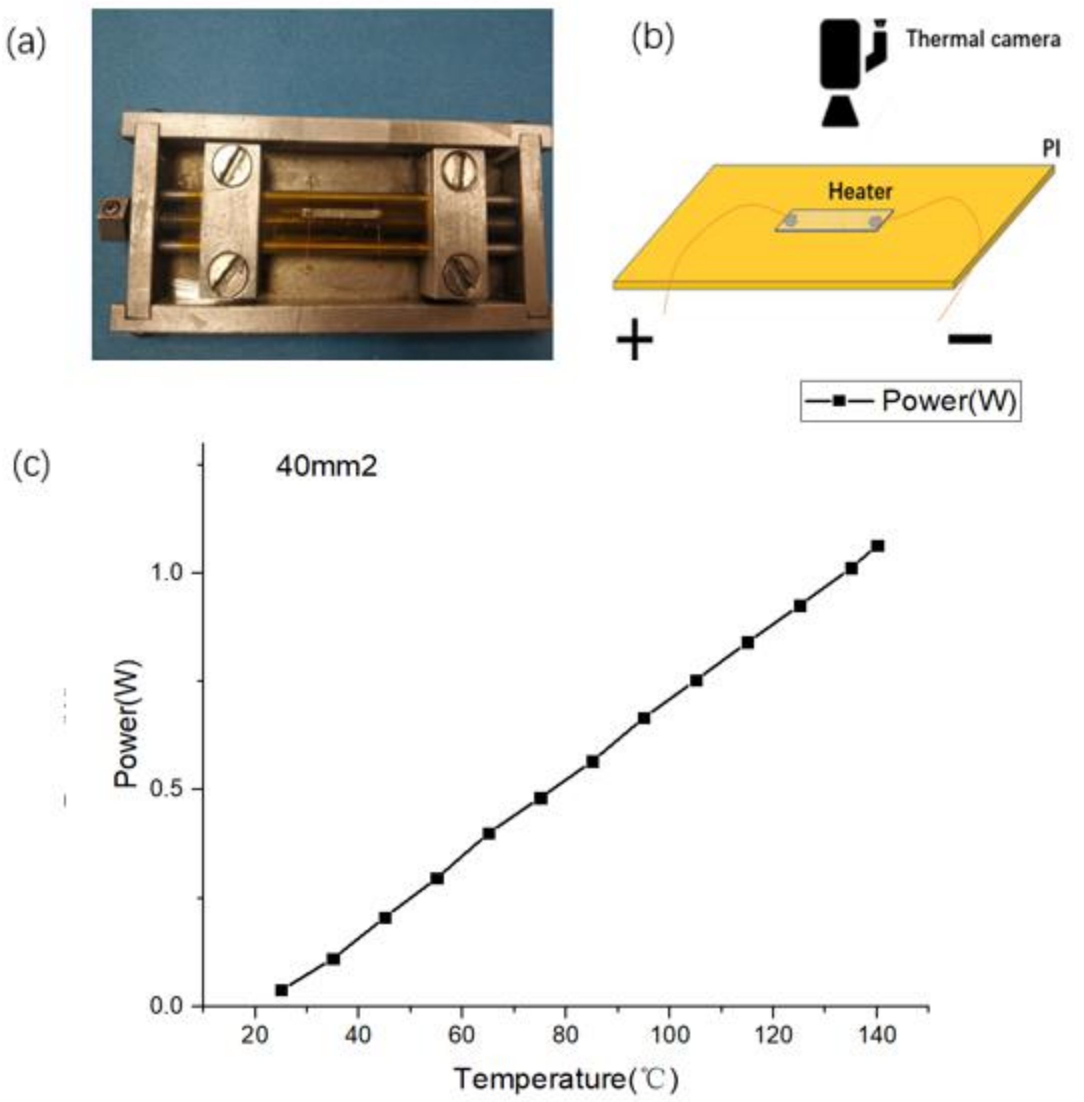

Figure 2.3 (a)The small work stage used for testing, PI tape is suspended with the heater attached on. (b) Thermal camera is used to record the temperature variant with time. (c) The tested temperature-power figure, it shows a relatively linear relationship between temperature and heating power.

Figure 2.3 shows that heating power and temperature shows a relatively linear relationship. Based on the size and required temperature, heating power can be calculated conveniently.

CHAPTER III

Folding process and Dynamic analysis

3.1 Folding material

In this study, we use pre-strained polystyrene (PS) as folding material. It is commercial product made by Shrinky Dinks. Biaxial tensile strain is introduced during fabrication and is uniform in thickness direction. It is known that glass transition temperature of PS is about 100 Celsius, which is much lower than that of PI (410℃). During production, the polymer is stretched when its heated to a high temperature and cooled down quickly. When the produced polymer is heated above glass transition temperature, strain will be released, and polymer will shrink by 50% in both directions.

3.2 Folding mechanism

Figure.3.1 shows the designed experimental setup, heater is attached on SMP using polyvinyl alcohol (PVA). PVA is a water-soluble and soft glue. Using traditional superglue will introduce a large constrain to the surface of SMP, which will cause a downward bending [14]. PVA glue guarantees heater can be easily detach from the bended structure after heating and will not confine the deformation on the surface of SMP. As figure 3.3 shows, when PS is heated by AgNW heater, there will be a temperature gradient along the thickness of PS. Upper part which is closer to the heater has higher temperature than lower part, which causes upper part shrinks more in the same time. This uneven shrinking will lead to folding, and in this case the PS will fold upward.

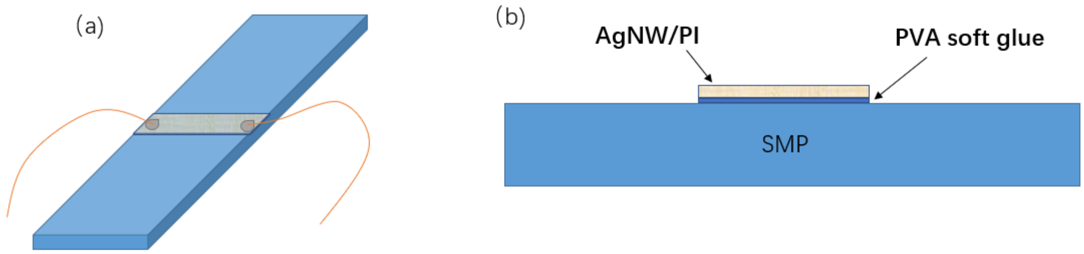

Figure3.1. (a) setup of folding structure process. (b) sideview of the set up. AgNW is half embedded in PI and heater is attached on PS by PVA soft glue.

The hinge of different folding angle is shown in figure 3.2. When the folding angle is small, shrinking area is limited in a small area within the heater. But in figure 3.2(d), (e) where folding angle is large, shrinking area expands. When the heating power is small, only the heater-covered area will be heated above triggering temperature, thus if large folding angle is needed, heating power should be more than triggering temperature requires.

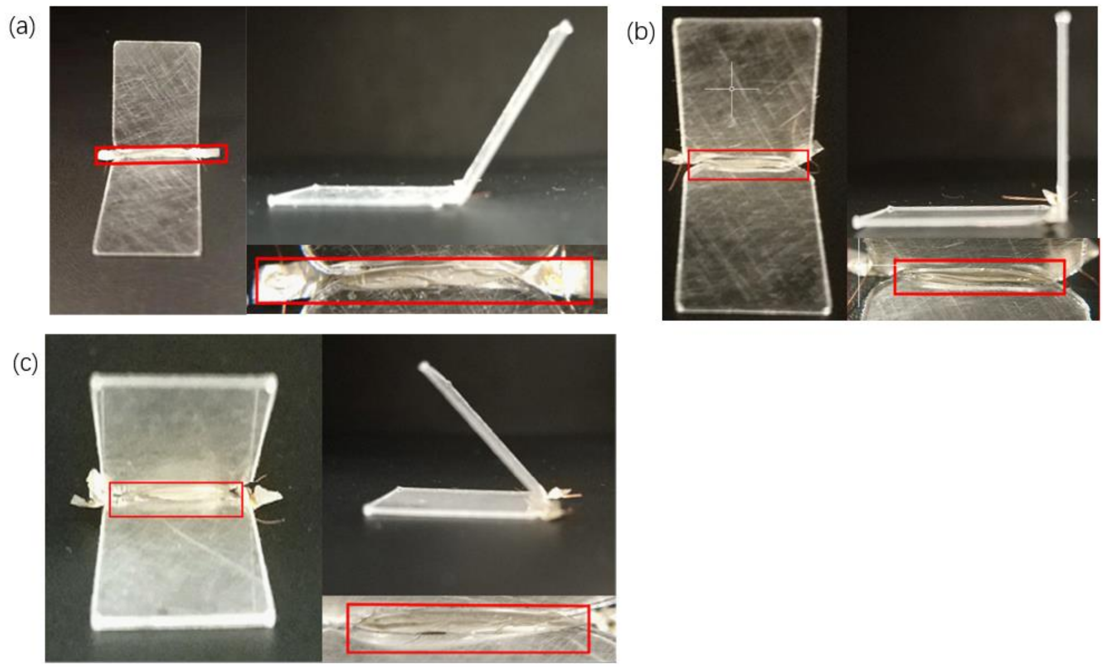

Figure3.2 (a)Folding angle=60°, heater keep attaching on the SMP. (b)Folding angle=90° shrinking area expands (e) Folding angle = 145° heater attaches with SMP, shrinking area expands

3.3 Finite element analysis

Thermal distribution is the triggering source in this research, and it is important to look into the detail of the thermal behavior of folding process. Unsymmetrical heating will create a heat gradient through the thickness direction, area closer to the heater shows a higher temperature compared with bottom area. Bending process is very sensitive to temperature. If heating power is so large, all material in heating area will melt and fail. Temperature control is required in this process and Finite element analysis of steady state thermal analysis is done by ANSYS version 17.1. Heater is fixed on the top of PS and is assigned with constant temperature of 130°C. Thermal conductivity coefficient is set to 0.03 W/m·K. Fig. shows the result of this simulation. On the topside, temperature stays 130°C and on the bottom side, steady-state temperature is about 127°C.

Transient thermal analysis shows the temperature change when assigned heat flux of 4500W/m² (corresponds to the power we applied on top surface). Triggering temperature is 115℃. During heating process topside first reach triggering temperature, which means the topside will shrink first and triggers folding. Material property used is listed in Table.1

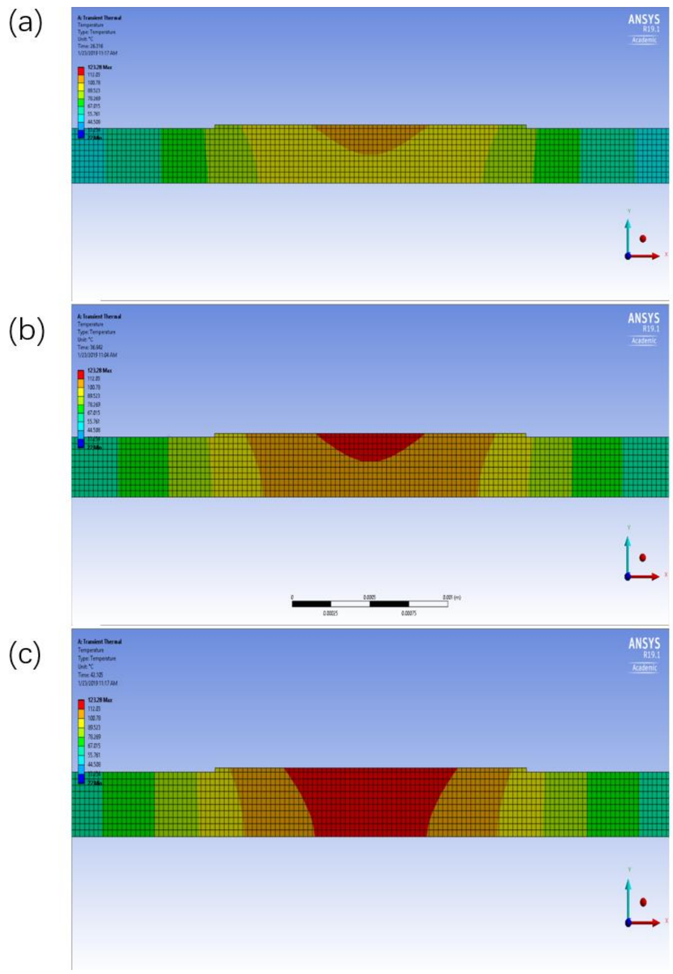

Figure 3.3 (a) At t=26.3s, SMP's top surface reaches triggering temperature, at this time, SMP starts folding. (b) t=36.8s, a temperature gradient exists along the depth direction, top surface and shrinks faster than the lower surface, folding continues. (c) t = 42s, most of the heated area is on triggering temperature, folding process stops.

Table 1 input material properties(polystyrene)

Thermal conductivity	0.14 W/m*K
Density	1050 kg/m³
Specific heat	1300 J/kg*K

3.4 Folding angle vs time with different input heating power

As in 3.2 we discussed when the folding angle is larger, there will be larger shrinking area near hinge. And FEA of the polymer shows the heated area is influenced by the heating power. When heating power is small, in the steady-state, the heated area is limited under the heater, but when the input power is increased, heated area grows and results in a larger shrinking area which potentially cause larger folding angle. A new experiment is done to see how the heating power influence the steady state folding angle.

Heaters and polymer are the same as the ones in 3.3. Polymers are heated under different heating power in room temperature. All the heater is cut as 2mm*20mm to guarantee the same total area, the folding process is recorded in video and folding angle is read from the recorded video.

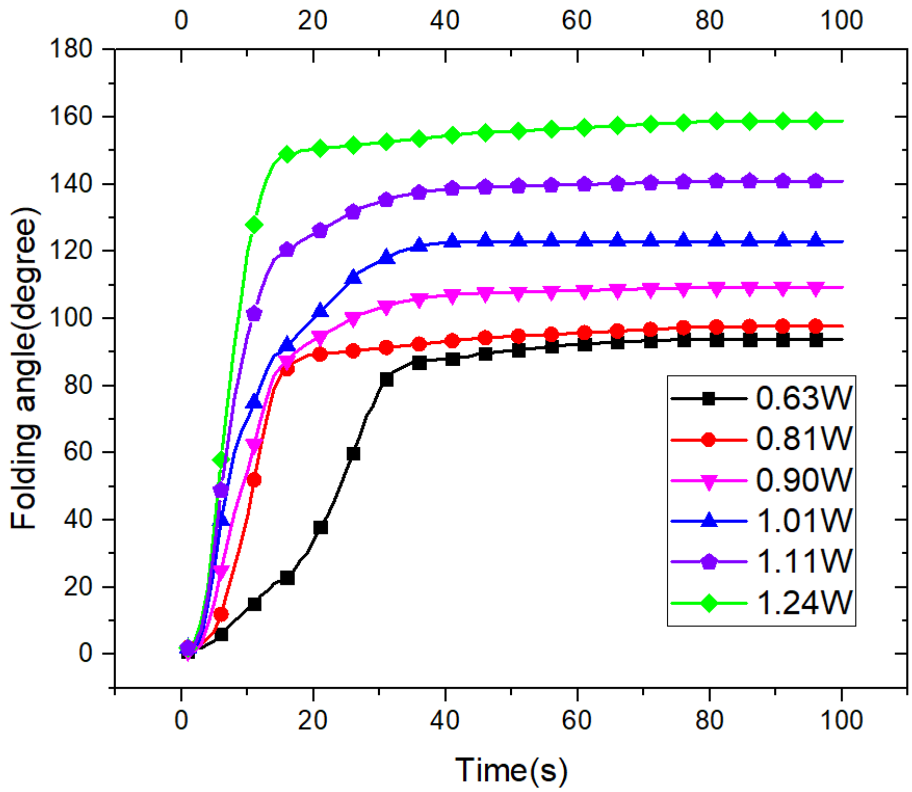

Figure 3.4 Folding angle vs Time. Experiments under six different power is done and recorded. Larger heating power gives a larger folding angle in steady state.

When heating power is below triggering power (0.63W), the folding process cannot start. This temperature may slightly vary (0.6-0.65W) under different ambient temperature and different attaching condition. Between 0.63-0.81W heating power, no significant steady-state folding angle can be detected but the folding speed keeps increasing. And when input power is larger than about 1.24W, the folding process becomes unstable. This figure shows the minimum heating power we need to create certain folding angle structures, and the folding behavior in the time domain. But note that if we want to create a accurate folding angle structure, we cannot control it using this figure because there’s some error between each experiments.

3.5 SMP patterning design

Since Folding is caused by shrinkage of SMP near hinge, a large strain will be introduced on heater as materials accumulates on hinge area. To solve this problem, special hinge patterning is designed. Like Fig3.3. shows, part of material is removed to promise there's enough space for folding process.

Based on the design, SMP are patterned to different plane shapes by laser cutter. A cube (figure3.2 b), a pyramid, or other shapes. Different folding angles are needed for different structure design. Folding angles are controlled by applied power and heating time. Heaters are attached on the red area by PVA glue in fig3.2. After heating, the PVA glue is washed by DI water as it is water-soluble. After that, it is easy to detach the heater from the SMP.

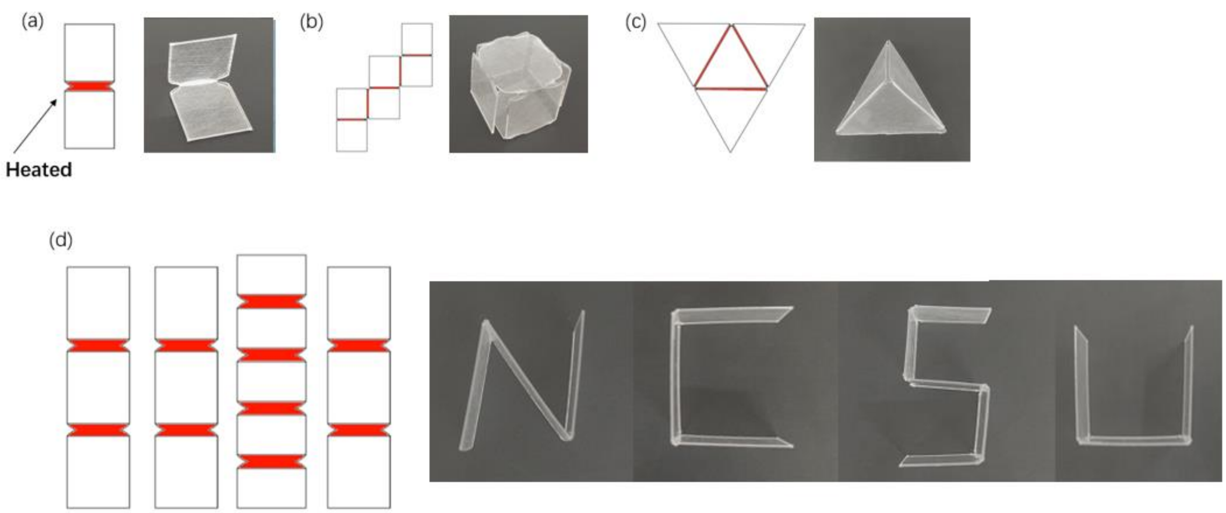

Figure 3.5. (a) Single folding unit, red area is heated. (b) Cube shaped pattern design (folding angle=90°) (c) Pyramid pattern design (folding angle=120°) (d) 'NCSU' shape pattern design

CHAPTER IV

Temperature control of wearable heater

4.1 Heater preparation

The wearable heater is designed by Zheng Cui in Dr.Zhu's lab. The fabrication process and material are the same as heater preparation introduced in chapter 2. It is a highly stretchable and conductive heater design for medical usage. The temperature of this heater should be controllable and be able to response to outer stimulation like temperature change.

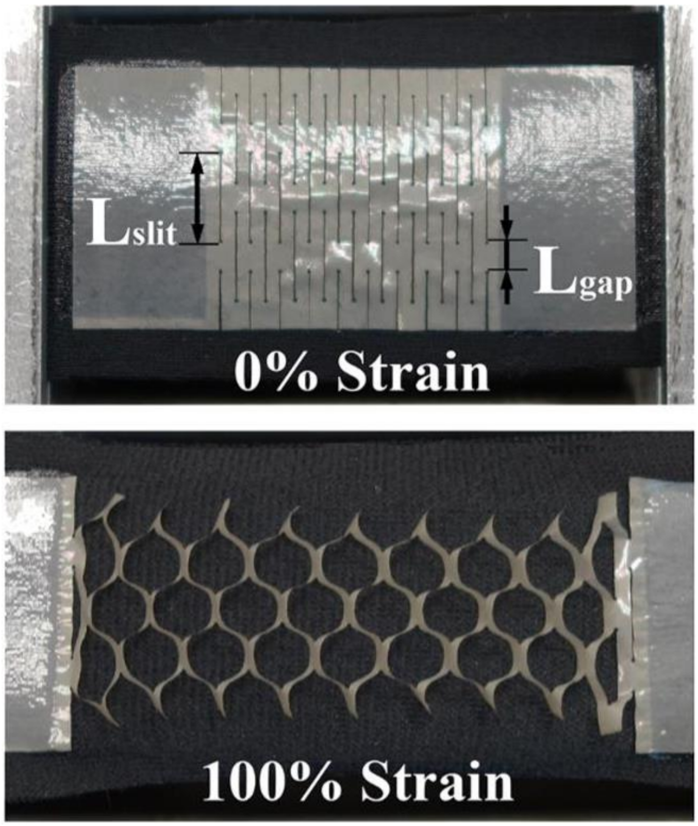

Figure 4.1 The designed wearable heater

4.2 Temperature measurement.

4.2.1 measurement circuit design

As a wearable device, it is not practical to measure its temperature by using thermal camera. Also, other auxiliary component like thermal couple or commercial temperature sensor will increase the cost and decrease its portability. An ideal measurement method should be as simple as possible. As a silver-Nanowire based heater, it has certain temperature coefficient of resistance (TCR). The resistance change of the heater corresponds to its temperature change. It is possible to control the temperature by controlling the power input based on its resistance change.

Circuit in fig.4.2 is designed for the control signal. By measuring the Voltage on R_0, then use equation (1) (2) and (3), temperature can be calculated in LABVIEW and then give feedback control to the heater. An DAQ controller (NI USB6211) is used for measuring the resistance as well as output control signal. The input is the voltage of constant resistor, and output is amplified and then connected with the heater. Calculation is done in LABVIEW, PC, the chosen resistor is 27Ω, amplifier chosen is from KH, Model 7600C. This control design has very high reading accuracy (0.001V) and maximum sampling rate, which satisfies the requirement of a wearable heater. Also, it is easily programable for different control mode with LABVIEW.

The control process is as following: first, DAQ send the measured voltage signal to LABVIEW. LABVIEW code will automatically calculate the resistance on that sampling time and send the voltage signal to PID controller. PID controller will increase or decrease current output signal. Output signal is amplified and applied on the heater. This loop can adjust the output power according to the set temperature and measured temperature. Sampling rate is set to 500 HZ, but the whole loop includes input, calculation, and output process which takes time.

Specific time for one loop is in the range between 0.135s and 0.140s, and this response rate is good enough for the wearable sensor.

$$Rx = \frac{V2-V1}{V1} * R1 \quad (1)$$

$$T = T_{room} + \frac{\Delta R}{R0} * TCR \quad (2)$$

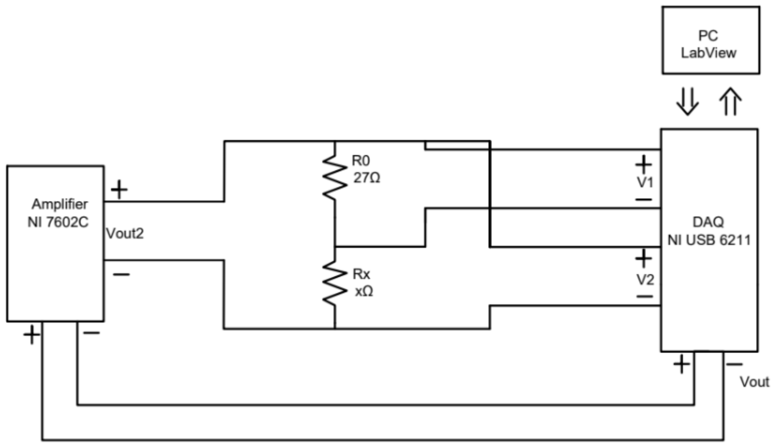

Figure 4.2 Real-time control circuit of heater, (Rx is the heater). Voltage on R0 is measured and DAQ is used for signal collection and output. In PC, LABVIEW is used for calculation and signal processing. V2 is the output voltage.

4.2.2 Heater's TCR measurement

Based on the temperature-measurement method, TCR of the heater is a key parameter. Tests of two heating method is done: outer source heating and self-heating. Heaters is attached on the glass plate, and thermal couple is fixed on the heater to measure the temperature in real-time. In the outer-source test, the glass plate with heater is put in the oven, and multimeter (34001A, Keysight Technologies) is used for measuring the resistance of the heater. In the self-heated test, the heater is connected with power supply under different Voltages to control the temperature, and the resistance is calculated by the voltage and current.

Results

Figure 4.3 shows the results of Cycle-heating. Three cycles of resistance-temperature tests are done. There is no significant resistance change between each cycle, and average TCR is calculated from T=T0+(R-R0) /（R0*TCR）. In the test of oven-heated heater, average TCR is 0.0034 per degree C, and in the test of self-heated heater, average TCR is 0.0032.

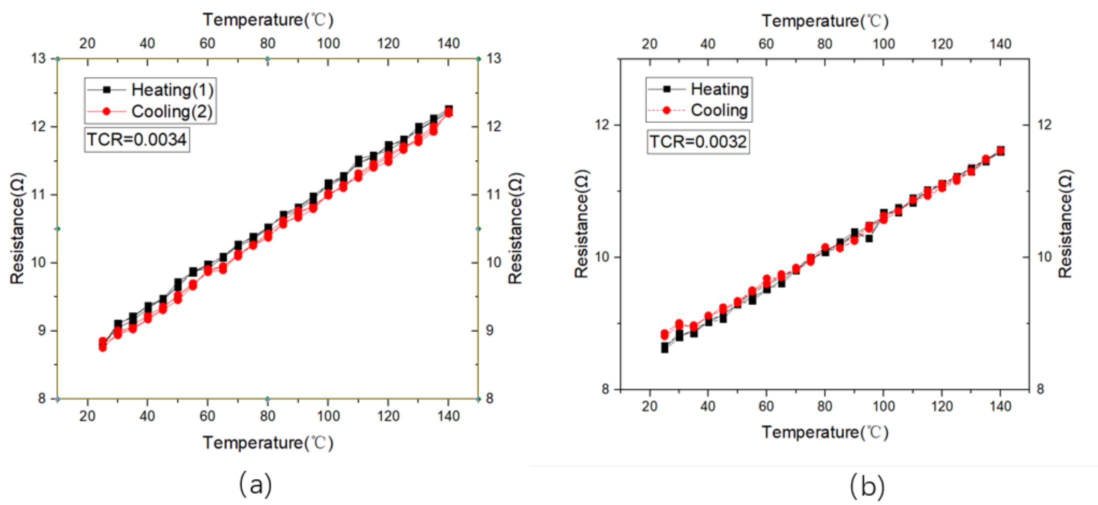

Figure 4.3 Measurement of Temperature-Resistance figure. Each experiment is done 3 times from heating to cooling. (a) Oven heating, TCR = 0.0034 (b) Electric heating TCR = 0.0032.

4.3 Heater testing

First, heater is fixed on the work stage which separate the heater from attaching any thermal conductive surface. And set the desired temperature (35℃) in LABVIEW. Real-time temperature and output Voltage are recorded in LABVIEW. Fig. shows the tested results, after applying voltage, temperature increase to the set value fast. And then temperature oscillates within certain range. Light bulb above the heater is turned on later, and this outer heat source does not have much effect on the measured temperature. This system response to the outer heat fast so that the output voltage change compensates the environmental stimulation.

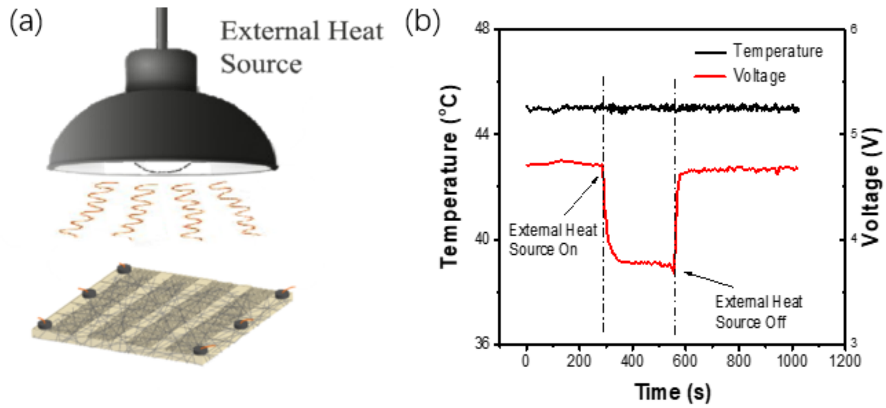

Figure 4.4 (a) An 50W light bulb is used for additional heater, it is set above the heater to apply additional heat. (b) The test results, when the light is turned on, an obvious voltage drop is detected but temperature stays in the set point. And the voltage increases to previous level when the bulb is turned off.

In the next step, the set temperature is changed over time, and measured temperature as well as output voltage is measured by the system. From 30℃ to 45℃, 5℃ one step, the temperature is increased step by step and then decreased. From the tested figure, the response for the temperature change is fast and there's no obvious over shoot in this control.

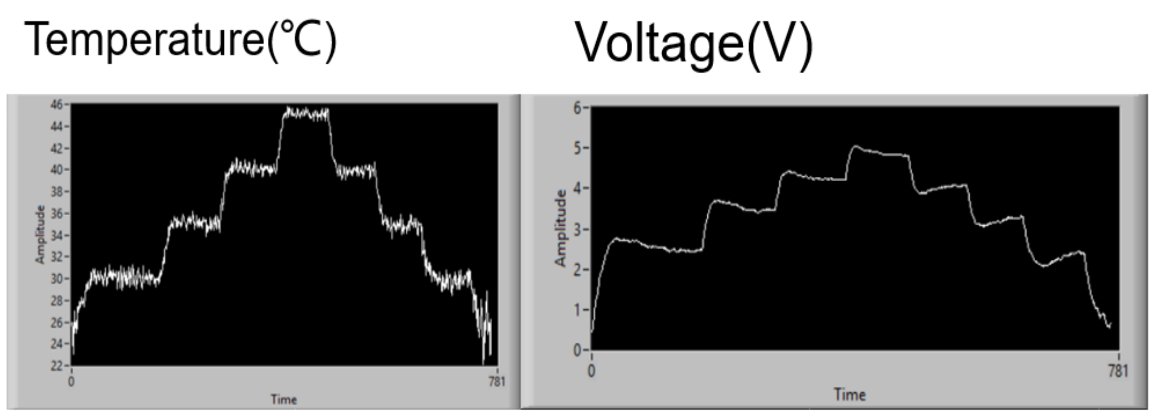

Figure 4.5 Temperature-voltage response after changing the set temperature. One sample time approximately equals to 0.13s. The temperature and voltage response is fast and temperature is well controlled within ± 0.5℃ accuracy.

Based on the output power limit of the amplifier we used, the temperature range of this specific wearable heater design is 25℃ to 50℃ . The experiments are done in oven, which separate the heater from outer wind or temperature change. The response time(0.13s) is mainly caused by the commuication time of the USB3.0 interface. As a heater, this response time is good enough to control the temperature in ±0.5℃ range, which is neglictable to people's feel. The stimulation test is designed for the ambient temperature change. For example, when people move from outdoor to a building, it is expacted to be a temperature change. And the heater should response to this ambient temperature change and self-adjusts heating power to maintain the set temperature.

CHAPTER V
Conclusions and prospects

In summary, embedding silver Nanowires into substrate polymer, a flexible and highly conductive heater is manufactured. Based on the accuracy requirement and its application, three temperature control method are introduced and tested. In the non-feedback control mode, temperature-voltage and temperature-current curve is tested and compared. Thermal camera is harnessed as temperature measuring tool. And in the feedback control method, LABVIEW and NI DAQ is applied, and temperature is calculated and controlled using PID controller. This method can realize an accuracy of ±0.5℃, and the response time is about 0.5s, which are good enough of a heater.

A self-folding experiment is designed using pre-strained shape memory polymer and designed heater. Shrinkage triggering temperature is measured and using voltage control, and the folding angular speed under different input power is investigated. FEA analysis of the simulated model shows the transient temperature distribution, higher power of the heater will induce a higher maximum temperature and wider heated area. These will have different influence on the folding process. Higher maximum temperature will cause a faster folding process and wider heated area will increase the final folding angle. This may be a way to control the folding angle.

The designed folding process shows its prospects in self-assemble 3D electronics. Sequential folding[15] realized by sequentially heating of designed pattern, is now a new trend of origami-inspired fabrication process. Compared with light heating, electric heater can provide more power, and the heat will be more focused, which means higher efficiency. In small scale, many researches have been done for self-assembly micro/Nano scale electronics. And heating is a common triggering method for folding [25]. The designed heater is good for small scale 3D electronics as the Nano-wire based heater keeps functioning in small scale. Currently the limit exists in laser cutter's tracing width(~270μm). Before applying this method to small scale self-assembling, more accurate cutting method need to be proposed. Photolithography, which is a used for create extremely small-scale patterning design, can be good enough to pattern the shape of heater.

Wearable heater has potential in both commertial textiles and medical uses. There're many commercial heaters sold by different companies. Most of these heater are chemical based, for example, when water is mixed with quickmime, a lot of heat will be released that is able to cook eggs. Commertially avilable eletric heater is using heating wire, which cannot be made in normal textiles, because the heating wire is not flexible enough. This paper introduced a highly flexible wearable heater that it is possible to integrate in the normal textile, and people are able to adjust the temperature by their needs. The future work could be applying this control method to a microcomputer. As in this design, it is still in experimental environment, a PC and amplifier is needed, which makes our heater not portable. If we use microcomputer to control the voltage, practical and portable heater could be created.

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