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Textile-Based Thermally Driven Actuators for Soft Robotic Mechanotherapy Applications*

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Abstract— **Rigid-body industrial robotic manipulators and pneumatic compression systems are widely used in mechano-therapeutic applications. However, rigid and bulky components reduce the wearability of the system in mobile environments. The current trend in wearable robotics tends to build such devices using textiles/silicone materials thanks to their lightness, compliancy, and comfort properties. In this study, thermally powered soft fluidic actuators that utilize liquid/gas phase transition property of low boiling point liquids are investigated. Proposed actuators generate desired pressure level and have great potential to free mechano-therapy devices from such bulky components. The developed structure incorporates textile-based heaters, thin film actuator shells, and low boiling point liquids. Here, two low boiling liquids with different boiling temperature are mixed successfully in order to obtain desired boiling point. Results a revealed that actuators constructed with PE/PA membrane did not show any deterioration even after 500 cycle actuation. In order to control the system, instantaneous temperature of the textile-based heater on the actuator device is used as feedback for the on-off controller.**

I. INTRODUCTION

Soft Tissue Manipulation (STM) is a powerful and direct form of mechanotherapy, which has significant implications in physical rehabilitation, disease prevention, and health promotions [1]. Different types of devices for manipulating muscle tissue have been developed for clinical applications and pneumatic compression devices are already in the market and widely used [2]. However, these systems have limited control modalities and lack of monitoring the forces being exerted to the body during the application and previous studies have shown that the loading conditions of soft tissue have a crucial effect on the mechano-therapeutic treatment [3]. Therefore, alternative approaches including textile based methods are being considered in the literature. There are some STM devices using electrical stimulation [4] or pneumatic compression [5] to aid muscle recovery.

Pneumatic compression devices are quite commonplace to be used in STM. However, such pneumatic compression systems are tethered to bulky air tubes and air compressors. These type of therapeutic technologies limit mobility and comfort of the wearer restricting them to home or hospital environments. On the other hand, electronic textiles and wearable functional technologies have become a nascent market in recent years and textile materials have become more functional compared to conventional textile concept. A definition of this new technology can be stated as "Textiles that are able to sense stimuli from the environment, react to them, and adapt to them by integration of functionalities in the textile structure." [6]. However, bio-feedback systems and actuation that act in a direction from the textile are far less considered but we now see an enhanced interest for such kind of smart textiles where the textile is acting upon its surrounding e.g., giving relief from spasticity by antagonistic muscle stimulation technique [7]. Now a second generation of smart textiles is being developed, where the output is central, accompanying the first generation, where the focus was on input. Thus, moving from the current efforts in the area of smart textiles, in this paper we discuss the development of a textile-based actuator and its potential application in a robotic mechano-therapeutic glove with thermal actuation mechanism. The glove can be used for relief or treatment of daily muscle tiredness and fatigue due to computer/mouse usage and other reasons, conditions such as carpal tunnel syndrome, as well as other similar conditions and muscle treatment. The developed actuator can be used in other similar applications as well.

Main contributions of this paper can be stated as: (i) Design and development of textile dominated wearable mechano-therapeutic massage actuators using liquid/gas phase change actuation system and on-off controller with instantaneous temperature feedback; (ii) Creation of customized boiling point depending on the required temperatures by mixing two biologically harmless (low-toxic, non-flammable, safe) liquids at different rates to setup a mixture with boiling point slightly over human body temperature; (iii) Selection of textile based heat panel elements regarding

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to their energy efficiency and thermal homogeneity.

II. RELATED WORK

To date, soft pneumatic actuator systems are the leading technologies for the construction of soft robotics as assistive wearable devices [8]. Elastomeric materials such as silicone and rubber are used for the construction of pneumatic chambers [9]. While elastic materials give some superior properties such as heat, chemical resistance and the ability to conform to different range movements, some properties of elastomeric materials (material density, rigidity, strength) present challenges in wearable applications. Some recent studies introduced fabric-based actuators for the creation of the soft robotic gloves and pneumatic devices for the individuals suffering from a variety of neuromuscular disorders affecting to conduct everyday living tasks [10], [11]. Therefore, textile-based approach offers light, more compliant, low-profile and comfortable alternative than its silicone counterpart. There are, however, significant barriers to their widespread usage that need to be tackled. A significant number of components are still rigid within the system, even though these structures are referred to as soft robotic. A systematic approach is needed to transform rigid components into soft structures in order to create truly soft robotics as wearable devices or to eliminate their use by developing new technologies. Therefore, some previous studies focused on the development of soft actuators by utilizing liquid/vapour phase transition property. Miriyev et. al used ethanol within the pores of the silicone to expand the structure [12]. In their case, resistive wire was used as heating element to boil the liquid inside the silicone. In another study, Garrad et al. employed silicone and rubber urethane filled with Novec™ 7000 to create actuators and pump [13]. They used piece of conductive fabric as heating element. In a recent study in [14], thermally powered soft fluidic actuators (TPSFAs) are developed, which make the soft robotic device free from such bulky components. TPSFAs utilize liquid/vapour phase transition property of low boiling point liquids to generate desired pressure level for actuating. Through textile based-sensing and heating elements, the developed actuator demonstrates closed-loop feedback that enables dynamic pressure control in the presence of environmental temperature fluctuations. In this paper, we utilize aforementioned technology to develop soft robotic systems for mechano-therapy applications. With this objective, we also apply a simple on-off controller with instantaneous temperature of the textile-based heater on the glove as feedback.

III. THE MASSAGE SYSTEM

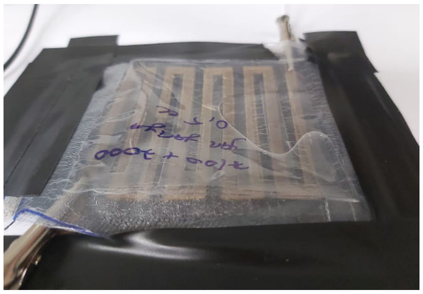
Our textile dominated, mechano-therapeutic glove with programmable actuation combining natural compliance to support muscle recovery and soft tissue regeneration can be given as an example for the massage system. The glove employs textile materials to achieve actuation with the help of phase change property of liquids for mechano-therapy applications. Fig. 1 shows the mechano-therapeutic glove worn by one of the team members. The glove structure has an inextensible fabric (woven) as a base layer for strain limiting property in order to exert all generated pressure to the soft tissue. Considering mechano-therapeutic pressure locations, heat panels are serially connected to a controller and the actuators are thermally bonded onto base fabric using fusible film. For closed loop temperature control strategy a temperature sensor is integrated onto the heat panel via stitching. The glove is wrapped around the wrist and secured using Velcro at a comfortable pressure. A mobile power bank is used to increase the temperature on the heat panels and eventually pressurize the bladder due to the evaporation of the liquid in it. The reader should note that the presented glove is just one potential application of the developed actuator. Below we first present the components and the properties of single sensor-actuator system, following which we also briefly discuss the two actuators integrated glove that can facilitate mechano-therapy.

Fig. 1: The mechano-therapeutic glove.

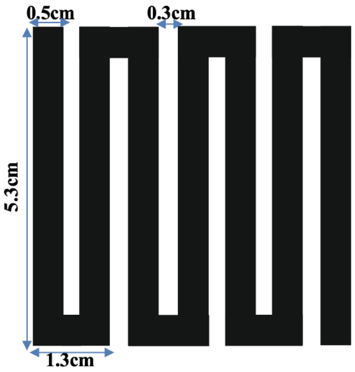
A. The Actuation Mechanism

1) Textile Based Heater: Heating panel of the actuator is designed and characterized using a silver plated knitted textile (Shieldex Medtex-130) via embroidering on denim woven fabric. Heating panel of the actuator is quantified based on thermal homogeneity. Demonstrating that the element heats up in a homogeneous manner is important for consistent actuation performance (in terms of force, response time etc.) and preventing hot spots. Heating is assessed using a thermal imaging camera (Testo 885). Figure 2 shows the textile heater. Figure 2(a) shows a photo of the heater itself, Figure 2(b) shows dimensions of the heater textile, Figure 2(c) provides an illustration of the heater with its components, whereas Figure 2(d) shows its thermal image during heating operation. As one can easily see from the figure heating is homogeneous during heating operation.

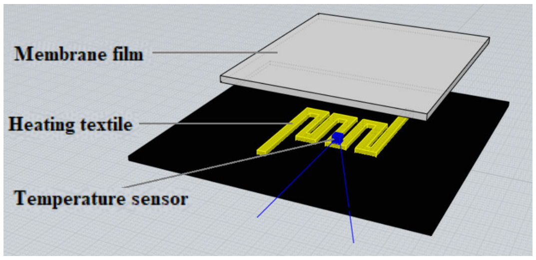
2) Membrane and Liquid: Since permeability of the membrane causes leakage of the liquid in gas phase, membrane selection for encapsulating the liquid for long term usage is important. We investigated the gas permeability of various membranes. Table I presents a summary of the permeability properties of the considered membrane types. Heat sealing performance of the membranes is also another criteria to



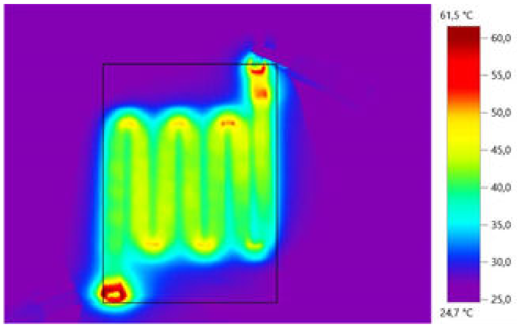
(a) Photo of the textile actuator.



(b) Dimensions of the heater.



(c) Textile heater, membrane, and sensor illustration.



(d) Thermal camera image of the heater.

Fig. 2: Textile heater.

TABLE I: Membranes and their permeability properties

Membrane type	Thick-ness (μm)	Oxygen permeability (cm^3/m^2)	Vapor permeability (g/m^2)	Fusing temperature ($^\circ C$)
TPE	38	85-646	-	121
TPU	50	85-646	-	121
PET/PE	76	180	<15	145-155
PA/PE	70	123	<15	135-150

select the optimum performing membrane. For example, although BOPP (Bi-axially Oriented Polypropylene) membrane has less gas permeability, it becomes easily brittle when fused that causes gas leakages. Table II presents weigh measurements of four membrane types after each inflation and deflation cycle. The table shows that, even after 5 cycles, TPE (Thermoplastic Elastomer) and TPU (Thermoplastic Polyurethane) membranes show poor performance in terms of gas leakage. It is observed that PET/PE (Polyethylene Laminated Polyethylene Terephthalate) membrane shows gas leakage in long term and it also has a crinkling structure as a bad feature. On the other hand, PA/PE (Polyethylene Blended Polyamide) film reverts to its original form in a short time after the heat press process finishes, the liquid can be injected easily using a syringe and heat press machine. Note that Table II shows a 5 cycle experiment with waiting times between experiments. Even a 5 cycle test shows that we can cancel two alternatives. Based on the obtained membrane performance results, PA/PE type membrane is chosen since two layers of PA/PE thin films can be thermally bonded together using heat press machine creating a pocket and also they can be thermally bonded onto the heat panels easily. With the help of a syringe, low boiling point liquid is injected into pockets and the created hole is thermally sealed. Two low boiling liquids; Novec™ 7000 (boiling point: 34°C) and Novec™ 7100 (boiling point: 61°C) are used due to their non-flammable and low-toxic properties for validation of the actuator performance.

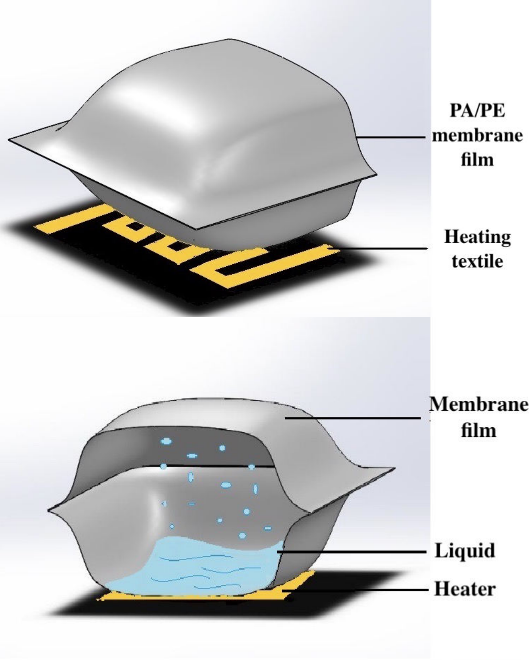
TABLE II: Actuators weight measurements for gas leakage

Cycle No	TPE (g)	TPU (g)	PA/PE (g)	PET/PE (g)
1st Cycle	2.83	2.17	2.92	3.72
5th Cycle	2.79	2.16	2.92	3.72

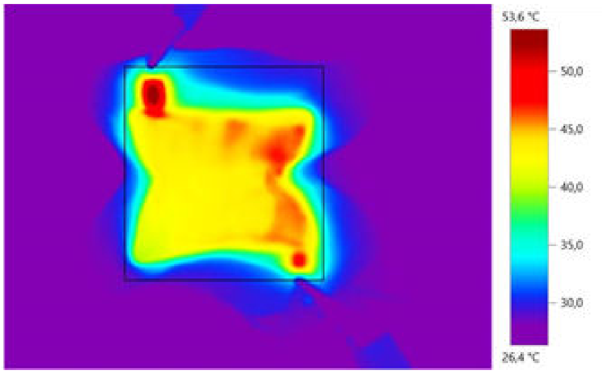
An illustration of the membrane with liquid and a thermal camera image of the swelled membrane are given in Figure 3. Thermal properties in terms of uniformity and temperature of the membrane as well as its swelling properties are found satisfactory for further implementation. During the experiments and thermal camera observation given in Figure 3(b), mixture of Novec™ 7000 / Novec™ 7100 liquids were used at the ratio of 3:2 in volume as

$$T_{mix} = P_1 T_1 + P_2 T_2 \tag{1}$$

where $T_1 = 34°C$, $T_2 = 61°C$, and $T_{mix} = 44.8°C$ denote the boiling points of Novec™ 7000, Novec™ 7100 liquids, and the mixture of them, $P_1 = 0.6$, and $P_2 = 0.4$ denote volume percentage of Novec™ 7000, and Novec™ 7100 liquids, respectively. Surface area temperature distribution graph of the actuator at the boiling point of the liquid mixture is given in Figure 4 with minimum $28.5°C$, maximum $53.6°C$, and average $39.8°C$. As can be seen from the figure, the temperature distribution is mostly gathered around the average temperature value, thus, the system can be considered mostly uniform. The reason for choosing this ratio and



(a) An illustration of liquid inside membrane.



(b) Thermal camera image of the swelled membrane.

Fig. 3: The membrane and liquid.

average $39.8°C$ is that, the average body temperature of a human is $37°C$ and a gap of $2-3°C$ is left to let the Novec mixture concentrate again after the heater is turned off.

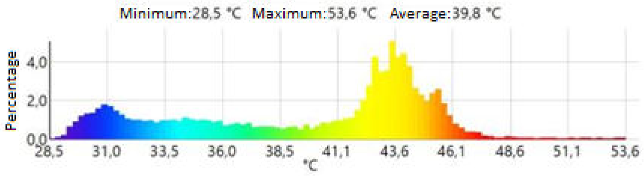


Fig. 4: The surface area temperature distribution of 3:2 mixture.

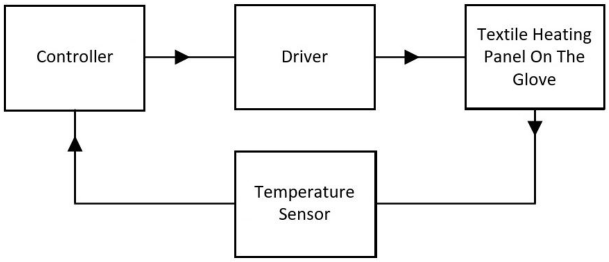


Fig. 5: The heat panel temperature control system block diagram.

B. Sensing, Modelling, and Control

Figure 5 shows a block diagram of the temperature control system for the heat panel. On-off controller is used with instantaneous temperature of the heater on the actuator as feedback where lower and upper temperature limits are set to 41°C and 44°C, respectively. The control loop strategy is, if the temperature falls down under 41°C, the heater powers on, and if the temperature rises above 44°C, the heater powers off. One issue preventing full utilization of other type of controllers is that there is no cooling mechanism in the system. In other words, the actuator can be inflated through a textile heater, however, it cannot be deflated through a cooling action. Instead, one needs to wait for the system to cool down and deflate. In future studies, incorporating a cooling mechanism will allow implementation of better control mechanisms as well. We have utilized MATLAB System Identification Toolbox for obtaining a mathematical model of the system utilizing its input and output data and obtained a model with 2 seconds of temperature delay (due to sensor and computational delays, and heater fabric property) as

$$\frac{T(s)}{I(s)} = e^{-2s}\frac{0.004}{s^3+0.1s^2+0.004s} \tag{2}$$

where $T(s)$ is the heater temperature and $I(s)$ is the input electrical current expressed in Laplace domain. The length of the data set to determine the model is 186 samples (i.e. 372 seconds). Electrical power is applied to the heater until it reaches to a desired reference temperature value. The desired temperature value corresponds to a desired force (or pressure) value that the actuation mechanism applies. The reference temperature values corresponding to desired force values were determined empirically utilizing a trial-and-error methodology. In the initial prototype circuit, an NPN BJT was used as electrical actuator. However, due to circuit stability issues, it was replaced by an H-bridge driver. As a potential future direction of study, we plan to incorporate a cooling mechanism and more adequate control strategies.

In this study, a Bluno Nano board is used as controller and a L298 mini board without an aluminum cooler is used as the driver of the electric circuit. In case of alteration, an Arduino Nano or an Arduino Uno board can also be used with same operating voltage, circuit setup and program code. The observed rate of current/voltage at the swelling state is 0.4 A / 5 V = 0.08 S. This rate depends on the impedance of the textile heater.

A digital thermometer, DS18B20, using 1-Wire protocol with approximately 100 ms response time (93.75 ms for temperature conversion and 2 ms write cycle time) is used as temperature sensor at 1 s sampling rate. This sensor can be connected to any digital input pin of the controller since the 1-Wire protocol is a digital communication protocol. A $4.7k\Omega$ resistor is used between the supply voltage and the output of the sensor to pull-up the sensor output with the 5V supply of the Bluno/Arduino Nano.

As there is a time delay of 1s in measuring the temperature (due to sensor and computational delays, which also contributes to the overall delay of 2s), there might be some difference between the measured and actual temperature values. Estimated maximum temperature difference between the actual and set limits is 4°C. In other words, the actual temperature might rise up to 48°C before the controller turns the power off. Also note that, the discrepancy between the actual and measured temperature values may change depending on the outer temperature and pressure. Since the total time required to toggle a GPIO pin to turn on and off the actuator and computational processes of the controller are so much shorter 1 second, they are included in the total 2 second delay, using the timers of the control unit.

IV. EXPERIMENTS, RESULTS, AND DISCUSSIONS

A test rig to measure the pressure of an actuator with a textile heater pair established consisting of a force gauge with serial port output that can measure the force value in Newtons. A 3D printed measuring tip has been produced and attached to the measuring end of the force gauge, so the force value can be converted to pressure value knowing the area of the tip (the area of the tip must be less than the area of the actuator).

The influence of dynamic strain on the PE/PA membrane after 500 cycles of inflation and deflation is investigated to see effect of repeated conditions actuator performance. A photograph of the test rig is given in Figure 6.

The test took 3.5 days, each inflating/deflating cycle taking 10 minutes (5 minute heating up and 5 minute releasing). Recorded experimental results at the beginning and after the test are shown in Figure 7. Note that the values below 5 N are shown as zero since the force gauge can't measure the forces below 5 N in the current configuration. As seen from the figure, there seems to be no significant difference between the overall cycle dynamics in the first cycles and the cycles after the experiment composed of 500 cycles and also no significant change was observed in the visible physical condition of the actuator. The magnitude of the cycles are close to each other at steady state (after the heater sufficiently heats up). We think that the small difference ($\sim$10 kPa) in the peaks of the cycles in the two figures is due to the change in the outside conditions (such as temperature difference between night and day) during the 3.5 day experiment since the lower extrema are also shifted.

The time delay between the reference and output is measured as 2 seconds, experimentally. During the ON phase of the on-off controller, a voltage of 10 V is applied to the heater and at this voltage, an average of 0.9 A current measured through the heater.

Fig. 6: A photograph of the test rig.

The obtained values representing the force are converted into pressure values utilizing

$$P = \frac{mg}{A} \tag{3}$$

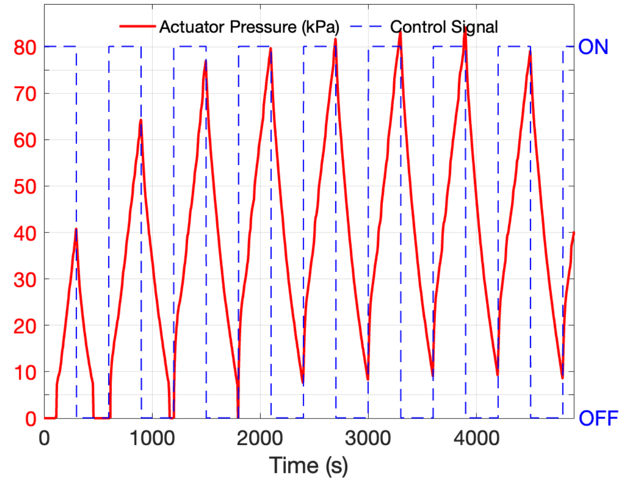
where P denotes the pressure, m represents the instantaneous measured mass, $g = 9.8m/s^2$ is the gravitational acceleration, and $A = 7cm^2$ is the area of the measurement tip exerting pressure on the force gauge.

Note that estimates of maximum tolerable and comfortable pressure of orthoses are typically around 5 kPa (i.e. 0.5 N/cm^2) and the peaks or magnitutes of the waves on the Figure 7 are not the upper pressure limits of the actuator [15], [16].

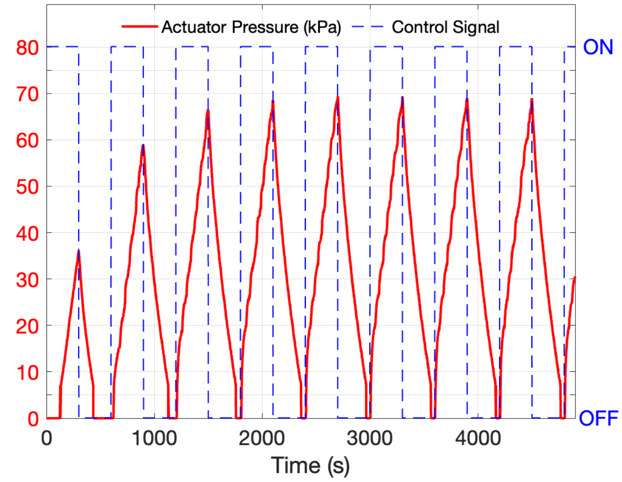
Results show that proposed actuators generate desired pressure level and have great potential to free mechanotherapy devices from bulky components. Thanks to the low power consumption of these actuators, wearable soft robotic mechanotherapy devices can work with only a small 10 Watt powerbank widely available in the market where similar gloves require a pneumatic valve and pump, so they consume more power and are heavier [10], [11]. A 5000 mAh battery was enough to run the therapy more than 4 hours. The mechanotherapy glove produced was appreciated by the users and has been awarded.

V. CONCLUDING REMARKS AND FUTURE DIRECTIONS

In this paper, we showed a textile-based actuator with a mechano-therapeutic glove application utilising the technology of thermally driven liquid/gas phase change actuation.



(a) First 8 cycles of the 500 cycle pressure test.



(b) Additional 8 cycles after the compleation of 500 cycle pressure test.

Fig. 7: 500 cycle pressure test results.

We mixed two low boiling point methoxy-fluorocarbon-based engineered fluids Novec™ 7000 (boiling point: 34°C) and Novec™ 7100 (boiling point: 61°C) at varios rates. It was found from the experimental tests that the boiling point can be customised within the range of 34-61°C depending on the application requirements. PE/PA membrane was selected due to its gas impermeability, comformability, and compability with textile materials. In order to control the actuation of the glove, a temperature sensor was used for closed loop control strategy.

Future work will focus on the creation of actuating glove including its textile-based heating parts, actuator shells and integrated pressure sensors seamlessly using advanced knitting techniques rather than the temperature sensor, applying a suitable control strategy using the model of the actuators and textile based sensors. We also envision to use cooling devices within the structure to increase response time of the actuators during the depressurization.

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