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PHASE TRANSITION ACTUATORS INSPIRED BY PLANTS EXPLOITING SOFT MATERIALS MECHANICAL CHARCTERISTICS

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Abstract. Soft actuators make use of the mechanics and thus extreme deformability of soft materials such as silicone elastomers, acrylic rubbers or natural rubbers. While experimental scientist create a plethora of soft robotic demonstrators exploiting high extensibility, strain stiffening, deformation by electrical charges, … etc. these devices rely on trial and error. This paper recaps two soft robotic approaches inspired by plant motions based on swelling/shrinking and mechanical instabilities using two materials, silicone rubber and natural rubber. It further highlights the similarities in actuation and yet differences in mechanical behavior of the two materials used and the challenges upon pushing towards miniaturization, fabrication and applications.

Key words: Soft robotics, phase transition, mechanical instability, elastomer, experimental

1 INTRODUCTION

Soft actuators represent a novel evolution of robotics inspired by nature [1]. Aiming at mimicking motions of human muscles, muscular hydrostats of animals or plants [2], soft robots are, in contrast to its rigid counterparts, based on inherently soft materials such as elastomers. Their mechanical properties i.e. Young`s modulus ranging from several kPa to a few MPa, Poisson ratios of 0,49 [3] are comparable to biological tissue such as muscles, skin and ligaments [2,4]. Owing to this “softness”, actuation and deformation can happen throughout the soft robots’ structure and provide an unlimited number of degrees of freedom [1]. Due to this mechanical paradigm shift, actuation of this soft robots explores a wide range of physical stimuli and phenomena [5] such as pneumatics [6], electric fields [7,8,9], shape memory alloys [10], phase transitions [11,12] or mechanical instabilities [13,14]. This offers a wide field to play for scientists and engineers. However, striving for optimization of soft robots and utilizing the most energy efficient approach for actuation calls for profound understanding of soft material mechanics in general and rubber/elastomers, in particular. This paper presents two soft actuators inspired by the two main mechanisms identified for rapid plant movements [15] – swelling/shrinking and mechanical instabilities – exemplified by the Mimosa (*Mimosa pudica*) [16] and the Venus flytrap (*Dionaea muscipula*) [17], respectively. Both soft actuators operate upon phase-transition but utilize different soft materials whose

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respective mechanical properties are relevant for the actuation mechanisms of each actuator, thus highlighting the challenges faced due to the fundamental differences in materials used and the need for profound understanding and modelling of soft materials.

2 PHASE-TRANSITION ACTUATOR INSPIRED BY MIMOSA PLANT

The Mimosa pudica is a curious flowering plant that is well known for folding its leaves inward and drooping them when being touched or shaken and re-opening a few minutes later. To achieve that movement the Mimosa pudica uses a special structure called pulvinus hinge formed by antagonistically swelling and shrinking of adjacent cell layers [16]. We have developed a very simple phase-transition actuator concept inspired by the Mimosa plant.

Phase-transition actuators use the volume expansion of a material due to an induced change of phase as driving force. In our concept visualized in Figure 1, we electrically control an in-situ liquid-to-gas phase transition [11]. A cylindric cavity of 6 mm diameter and 3mm height containing a resistive heater (SMD resistor, 100 Ohm) and a low boiling point liquid is manufactured within a soft rubber block made from the silicone rubber polydimethylsiloxane (PDMS, Sylgard 184, Dow Corning) with a 10:1 mixing ratio by mold casting and precured at 50°C for 3 hours. The cavity is then sealed with a thin 80 µm thick PDMS membrane and another curing step at 50°C for 3 hours.

Upon powering the resistive heater (I=0.1A, V=10V) for 60 s with a 30 s break, the low boiling point liquid evaporates and the gas phase deflects the PDMS membrane into a semi spherical shape (see Figure 1a,b photos) with a maximum area expansion of 120% [11].

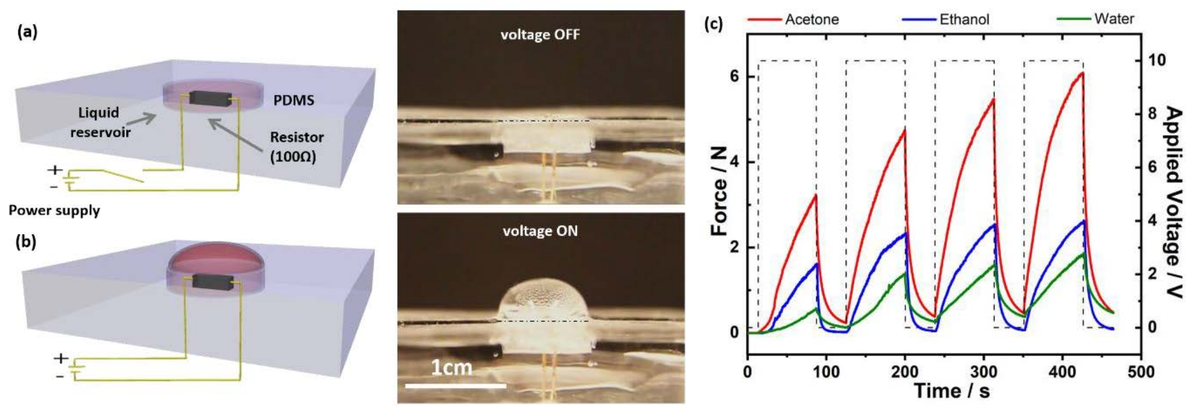

Figure 1: Phase transition actuator (PTA) design and achieved blocking forces:
(a) Schematic and photo of PTA consisting of a cavity containing low-boiling point liquid and resistive heater within PDMS casing, sealed with a PDMS membrane, that (b) is deflected by gas generated upon powering the resistor (adapted from [11]).

This deflection results in blocking forces (measured with a digital force gauge FMI 220B5 (Alluris)) up to 6 N upon using acetone (T_b =56,15°C), 2.5 N using ethanol (T_b =78,37°C) and 1.8 N using water (T_b =100°C) at 1 W power [11] (Figure 1c). The heating and associated evaporation is considered a fast process with achieving the maximum deflection of the membrane within 60 s during powering, making the actuation speed comparable with the

Mimosas pulvinus hinge whose actuation speed is about 20 s. Interestingly, also the cooling and subsequent condensation of the phase transition actuator is remarkable fast – returning to the base line within the 30 s of suspending the power as revealed by the blocking force measurements. Cooling of a liquid and subsequent condensation is typically a slow process. The unusual fast cooling behavior of the phase-transition actuator can be associated with the increasing tension and strain stiffening of the PDMS sealing membrane upon actuation and the "compression" seemingly aiding cooling/condensation upon suspending power. It is quite important to note here that the used PDMS Sylgard 184 exhibits a maximum elongation to break of about 135% with a significant stiffening from 80% strain on.

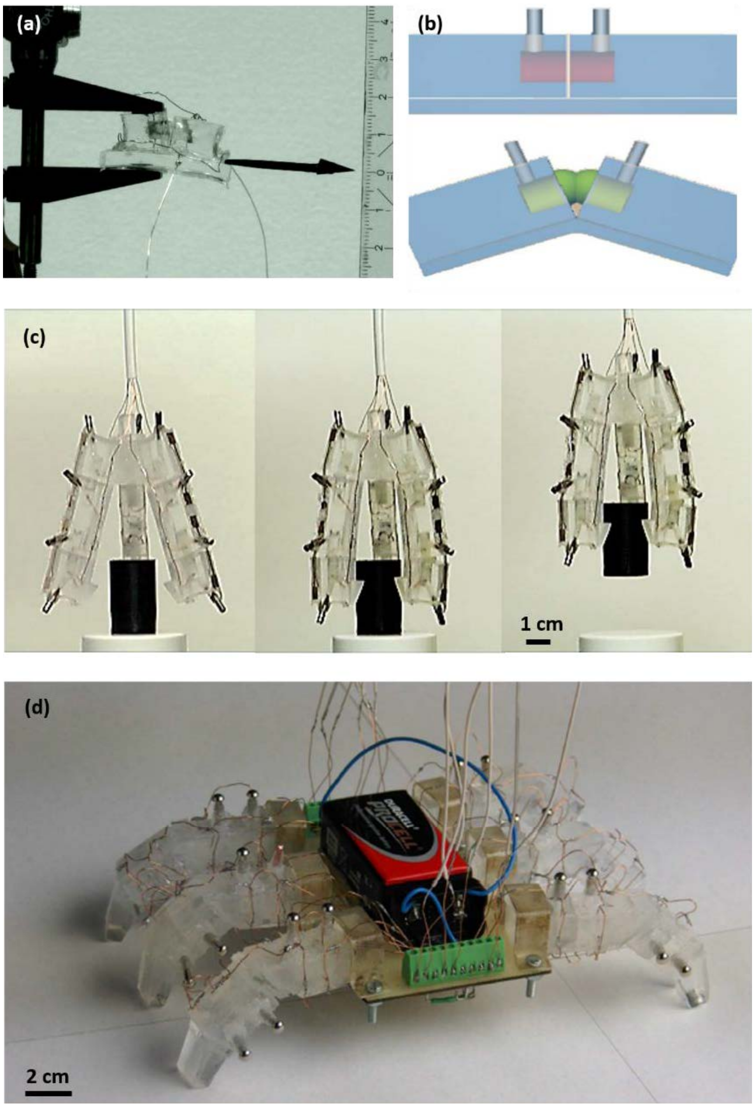

Figure 2: Phase transition actuator (PTA) applications for soft robots:
(a) Hinge structure based on (b) combing 2 PTAs facing each other on a common beam. (c) Soft robotic gripper using 3 arms and (d) 6-legged bug-bot based on PTA.

To highlight the potential of such a simple phase transition actuator, a hinge element inspired by the Mimosa`s pulvinus hinge is built: Two actuators are mounted on a joint beam facing each other – upon powering the deflected membranes are pushing against each other, deflecting the beam as shown in Figure 2a and b.

This design approach enables the fabrication of a simple gripper with 3 arms (Figure 2 c) where each has 2 joints for unidirectional bending and a more complex 6-legged bug-bot (Figure 2 d) where each leg has 3 joints and bends bidirectionally. For the hinges employed in these actuators a softer PDMS, Ecoflex 00-30 (Smooth-on Inc.) (with a Young's modulus of 0,1 MPa and a (uniaxial) elongation to break of >500%) is used for the membranes allowing larger area expansion when deflected. However, the softer membranes are more prone to diffusion (resulting in loss of low-boiling point liquid during gas phase) and also mechanical defects to high internal pressure (i.e. rupture).

A. Miriyev et al. took this phase transition actuator concept further, also using the softer PDMS Ecoflex 00-30 with an elongation of 500% and mixing in 20vol% ethanol to create a soft active foam-like material [12] that however also suffers from diffusion and failure issues mentioned above. R. Preuer evaluated alternate methods for inducing a phase transition such as inductive heating and microwaves [13].

3 ACTUATOR USING MECHANICAL INSTABILITY TRIGGERED BY PHASE TRANSITION INSPIRED BY THE VENUS FLYTRAP

The second plant inspired actuator relies on a mechanical instability mimicking the Venus flytrap (Dionaea muscipula) [14]. The Venus flytrap's trapping structure [17] is formed by the terminal portion of each of the plant's leaves with each of being deflected outward into a concave (open) shape while awaiting its prey. Prey in form of bugs touching the sensitive (trigger) "hairs" located on the inner surface presented in the open (concave) state, triggers a mechanical instability causing the Dionaea's leaves to undergo a shape change into the closed (convex) form subsequently trapping the prey inside [17]. This conformation change due to the instability is as fast as 100 ms, while the recovery back to the open concave shape is achieved by means of swelling/shrinking and takes up several hours. Challenged by the speed of the mechanical instability a phase transition actuator utilizing a mechanical instability is conceived [14].

The Venus flytrap inspired actuator design is based on the mechanical instability that occurs during the inflation of a balloon made out of a natural rubber latex. The rapid change in the balloon size is triggered by the liquid to gas phase transition of a low-boiling point liquid [11]. Combining mechanical instability and phase transition enables a significantly faster actuation than that of the Mimosa inspired phase transition actuator. With an actuation speed of 4 ms the Venus flytrap inspired actuator even outperforms it's plant counterpart [14] with an actuation time of <100 ms.

The soft material of choice for mechanical instabilities is natural rubber [18] - and in a few cases also acrylic rubber is used [19] – where a membrane exhibits a N-shaped pressure-volume curve when inflated into a spherical (or balloon) shape (as shown in Figure 3 a). This p-V curve can be easily experienced when inflating a balloon and is well described in literature [18].

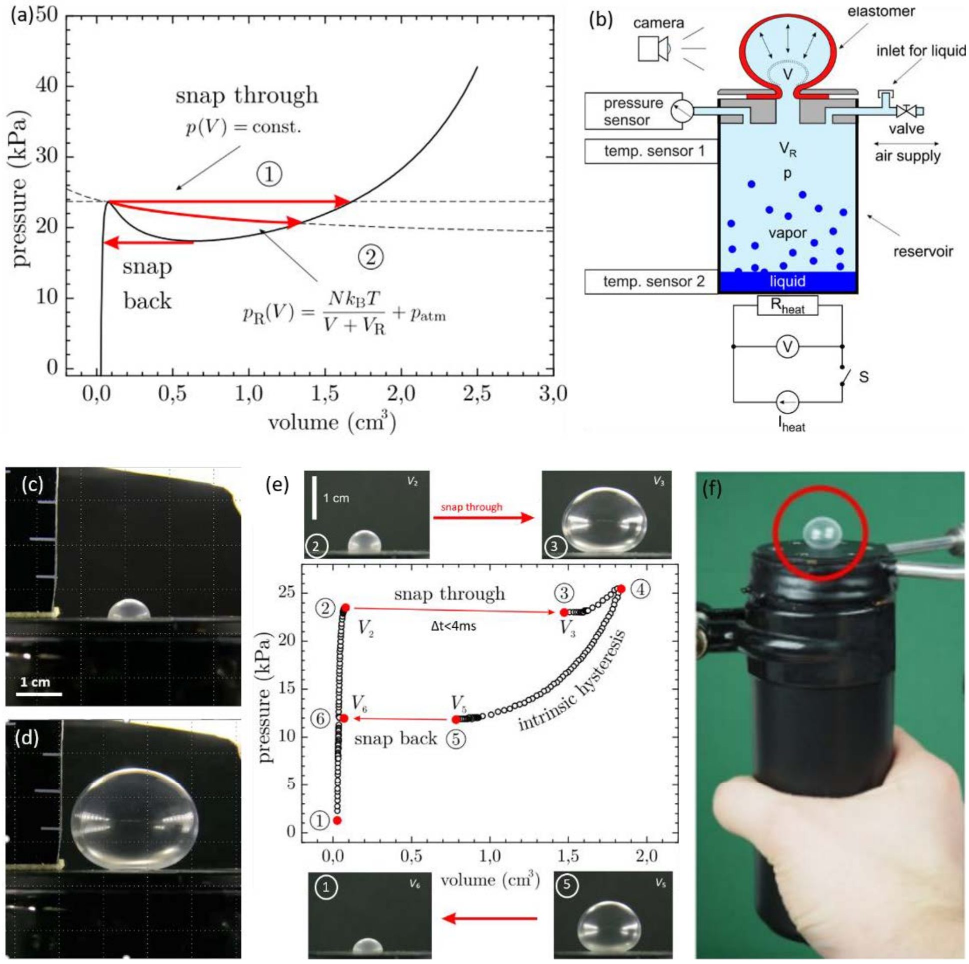

Figure 3: Actuator using mechanical instability triggered by phase transition: (a) N-shaped p-V curve of natural rubber latex balloon with snap-trough paths indicated in red (adapted from [20]) (1) at constant pressure and (2) gas hyperbolas when using an external reservoir. (b) Experimental setup consisting of a pressure reservoir (with a pre-adjusted pressure) additionally filled with low-boiling-point liquid, sealed with an inflatable elastomer membrane on top and equipped with Joule heating at the bottom [14], (c) inflated membrane before and (d) after snap-through instability with a 300% area expansion, (e) Measured data in the pressure-volume plane representing a full inflation and deflation cycle: Starting clockwise at state (1), pressure is increased up to state (2) where the phase transition is triggered by heating and the snap-through (state (3)) and snap-back (state (5) to (6)) instabilities are indicated with red arrows [14] and (f) size comparison with human hand.

The physical origin of the N-shaped dependence is a result of the mechanical properties where a balance between the free energy stored in the membrane by stretching and the work of pressure during the balloon inflation [14]. Starting with an initial small steep increase pressure resulting only in a small change in volume when the unstretched membrane is “stiff”, transitioning into a continuously increase in volume despite only a small further increase in pressure, until final another steep increase in pressure resulting in only minor changes in volume when the membrane almost stretched to its maximum stiffens again.

The curve is a direct result of the mechanics of the soft rubber material used – initially the polymer chains are entangled and the pressure increase starts stretching them (working against entropy), then after the network has expanded, only small changes in pressure allow further stretching the network until finally the network is almost ultimately stretched and thus stiffens (before ultimately rupturing).

A closer look at the p-V curve in Figure 3a reveals that after at a fixed pressure (24 kPa), there is not only one volume state (0,02 cm^3), but there are two volume states possible – the second being 1,6 cm^3. While continuously increasing the pressure results in moving along the pressure volume curve, a slight increase at the pressure at this point will result in a snap-through from the current small volume (0,02 cm^3) to the large volume (1,6 cm^3) coexisting at the same pressure. If the pressure of the overall system is kept constant, the snap-through instability (jump) from one state (pressure/volume, small) to another (pressure, volume, large) will follow a straight line. Experimentally, however, that is very challenging. When using a reservoir as a buffer, the resulting snap-through instability is not a straight line but follows the gas hyperbolas (Figure 3a). For the Venus flytrap-inspired actuator the reservoir is large compared to the volume of the inflated membrane, resulting in the relevant gas hyperbola almost being an horizontal line (Figure 3e).

The experimental setup [14] (shown in Figure 3b) for the phase transition actuator using an instability consists of an aluminum (beverage) can (providing a reservoir volume of 332 cm^3) connected to precision flow control valves (Festo GRPO-10-PK-3) used in the inlet/outlet line to achieve a controlled increase or decrease of the pressure. On top of the can an elastomer membrane with an average thickness of 60 µm made from natural rubber latex is clamped. Temperature is monitored by means of type J thermocouples at the top and bottom of the can reservoir with a heat transfer compound. The can is filled with a small amount of low-boiling liquid (acetone with T_b =56,15°C). At the bottom of the can two power resistors (12 Ohm each, connected in series) for resistive heating are located. The whole set-up is mounted inside a styrofoam box for thermal insulation. Pressure is recorded by means of a Jumo dTRANS p30 pressure sensor and volume is tracked by means of high-speed videos with 1920 x 1080 pixels at 50 fps and 640 x 360 pixels videos at 250 fps and evaluated with a Labview routine.

Figure 3 c shows the natural rubber latex membrane inflated at state (2) before and Figure 3 d right after the snap-through instability, resulting in an 300% area expansion. The pressure-volume curve shown in Figure 3 e show that upon slightly increasing pressure by means of a liquid to gas phase transition of the low boiling point liquid at state (2), the snap-through (red arrow in Figure 3 e) to state (3) occurs faster than 4 ms. Further increasing pressure results in following the pressure-volume curve, decreasing the pressure to state (5) triggers a snap-back (red arrow in Figure 3 e) to state (6).

The temperature to trigger sufficient pressure increase due to evaporation of the low-boiling point liquid and thus trigger the mechanical instability of the actuator is as low as 10°C – the temperature difference between room temperature (20°C) and body temperature (36°C).

The achieved actuation speed (<4 ms) is en par with and even faster than the speed of airbags deploying and this Venus flytrap actuator design holds great potential for ultrafast protective soft structures. Challenges for applications are posed on one hand by the fabrication and processing of natural rubber – being much more complicated than mold casting of silicone rubbers – and also the exact design, dimensions and pressure of reservoir and inflatable membrane as well as precise pressure control.

3 SUMMARY OF MATERIAL CHARACTERISTICS AND CONCLUSIONS

In summary, two plant-inspired soft actuators, both consisting of reservoirs sealed with elastomer membranes between 60-80 µm thickness employing phase transitions have been demonstrated [11,14]. Both phase transition actuators rely on inflation of an elastomeric membrane with area expansions of 135% and 300%, respectively relying on the mechanical properties of the elastomers used. Both the silicone rubber (PDMS Sylgard 184) and natural rubber exhibit a similar Young's modulus of ~ 1MPa, PDMS Sylgard 184 used for the simple phase transition has a rather low uniaxial extensibility for an elastomer (135%) with a steep incline and natural rubber latex used for the mechanical instability triggered via phase transition shows uniaxial elongations up to 800% with a very pronounced non-linear elastic behavior (Figure 4).

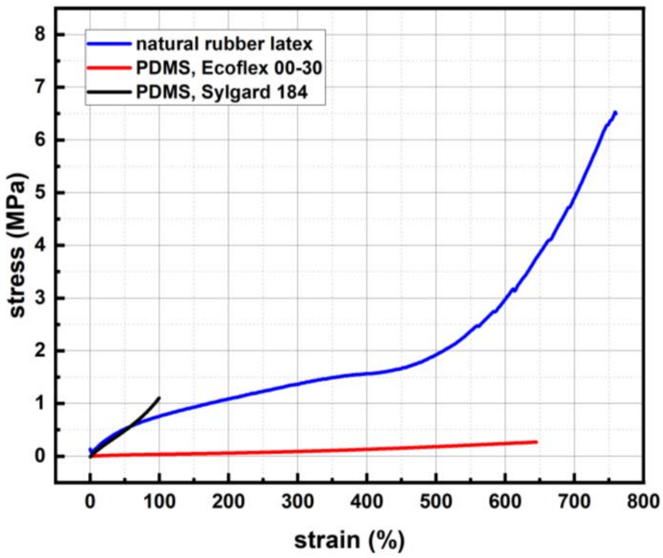

Figure 4: Stress-strain curves for PDMS Sylgard 184 and Ecoflex 00-30 as well as natural rubber latex.

PDMS Ecoflex 00-30 exhibits a significantly lower Young's modulus of ~ 0,1 MPa in comparison to PDMS Sylgard and natural rubber latex, also reflected by the extensibility being comparable to natural rubber, yet at lower stresses. Table 1 summarizes some material characteristics such as Young's modulus and elongation-at-break for the respective elastomers used. Figure 4 depicts stress-strain curves for the materials used, highlighting the significant differences in extensibility.

Table 1: Material properties for PDMS Ecoflex 00-30 (Smooth-on Inc., Macungie, PA, USA), PDMS Sylgard184 (Dow Corning Inc., Wilmington, NC, USA) (adapted from [21] and [22]) and natural rubber latex.

	Young's modulus E (MPa)	Elongation at break (%)
Ecoflex® 00–30	0,1	835
Sylgard™ 184	2,4	135
natural rubber latex	1,13	1000

Both material types – PDMS and natural rubber - find applications in soft robotics, however, PDMS (represented by Sylgard and Ecoflex 00-30) are available in a wide range of mechanical properties – this and their simple processing (by casting) makes them the most commonly used material as for experimental work.
However, to transition the simple concepts of these two plant-inspired phase transition actuators present in this paper into applications, it is necessary to have a profound understanding of soft material mechanics as well as their modelling. Such knowledge would facilitate linking physical models with the macroscopic mechanical properties of soft materials and thus facilitate appropriate material selection and device design e.g. for miniaturization tremendously furthering soft actuator technology and its translation into applications.

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