Plant-Inspired Actuation Strategies for Biorobotics

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***Abstract*—Plants offer a priceless source of inspiration for developing novel actuation systems for biorobotics. We tackled the osmotic principle at the base of plant movements to develop novel low-power-consumption actuators. Starting from modeling, we designed and fabricated osmotic actuators also featuring reversible actuation. We also studied faster plant movements where osmosis-based actuation is complemented by mechanical instability effects. Our related achievements are hereafter reviewed.**

***Keywords*—bioinspiration, osmotic actuation, biorobotics**

I. INTRODUCTION

Despite the remarkable progresses in the recent decades, actuation remains a bottleneck for the development of many robotic systems. In this regard, the Plant Kingdom provides a remarkable source of inspiration, since plant movements are widely recognized as impressive examples of low power consumption and energy efficiency. Indeed, combined with high actuation force and a rich movement repertoire, these aspects foster plant survival and adaptive growing in challenging dynamic environments.

Plants use a coordinated and reversible modulation of intracellular turgor (pressure) in order to tune their stiffness and achieve macroscopic movements. Being a kind of "natural hardness", turgor is generated by water (solvent) flux, as sustained by the osmotic pressure difference $\Delta\Pi=\Pi_i-\Pi_o$ between the osmotic potentials inside and outside the cell (subscript i and o, respectively). Such osmotic potentials are correlated to the concentration of osmolytes (solute), and the water flux occurs through an osmotic membrane ideally impermeable to solute (in natural plants, things are more elaborate: cell wall and plasma membrane behave as an osmotic barrier, solute rejection is not ideal and, more remarkably, solutes are actively transported).

We thus addressed the osmotic principle with the ambition to introduce a novel class of actuators for application in biorobotics. To the purpose, we enacted a research agenda structured as follows. First, we addressed osmotic actuation from a theoretical viewpoint, namely through a modeling study functional to model-based design [1]. We thus successfully developed an osmotic actuator [2], which also allowed us to address fundamental scientific questions regarding turgor formation in plants [3]. The as developed actuator was not reversible, being driven by the initial difference in solute concentration between two chambers containing water. We overcame this limitation by reversibly modulating the concentration of ions (acting as solute) in a subsequent embodiment, by further highlighting the potential application of osmotic actuation in soft robotics [4]. Finally, we carried out a complementary investigation. The speed of water transport in porous plant tissue is restricted by physical effects (poroelastic limit), yet plants manage to also accomplish faster movements by exploiting mechanical instabilities. We thus addressed this combined actuation strategy by studying hygromorphic bistable structures [5]. In the following sections, relevant achievements and selected complementary details are recalled from the cited studies.

II. MODEL-BASED DESIGN OF OSMOTIC ACTUATORS

In [1] we modelled the dynamic behavior of two exemplificative embodiments of an osmotic actuator concept, one transducing the actuation work by displacing an external elastic load, the other by inducing the elastic bulging of a circular elastic membrane. By recalling the van't Hoff formula for the osmotic potential Π, namely

$$\Pi = i\,R\,T, \tag{1}$$

where M denotes solute molarity concentration (we adopted sodium chloride, NaCl), i is the number of ions for formula unit, R is the universal gas constant ($R = 8.314\ \mathrm{J\,K^{-1}\,mol^{-1}}$), and T denotes absolute temperature, and by modeling the water flux q across the osmotic membrane as follows:

$$q = S\,\alpha\,(\Delta\Pi - \Delta p), \tag{2}$$

where S and α denote the surface area and the permeability of the osmotic membrane, respectively, and Δp represents the pressure difference between the two sides of the osmotic membrane, we introduced two ordinary differential equations whose direct integration fully described the actuation dynamics in non-dimensional terms. From said solutions we derived relevant scaling laws for the actuation figures of merit (i.e., characteristic time, maximum force, maximum power, power density, cumulated work and energy density) as a function of model parameters, and we concluded that in order to obtain a characteristic actuation time around 2 min (compatible with low-power biorobotics systems), the actuator characteristic size should have been around 10 mm.

In [2] we carried out the detailed design and fabrication of the osmotic actuator (Fig. 1). Model predictions were fully matched. The actuator featured a low power consumption (on the order of 1 mW) and forces above 20 N (through the bulging of a 5 mm diameter membrane). Compared to existing (low-power-consumption) actuation technologies, it also featured a remarkable energy density.

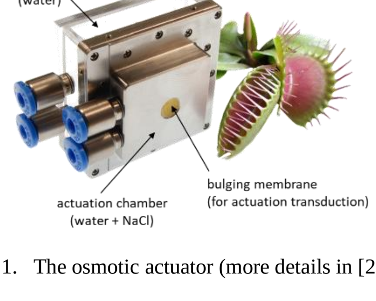

Fig. 1. The osmotic actuator (more details in [2])

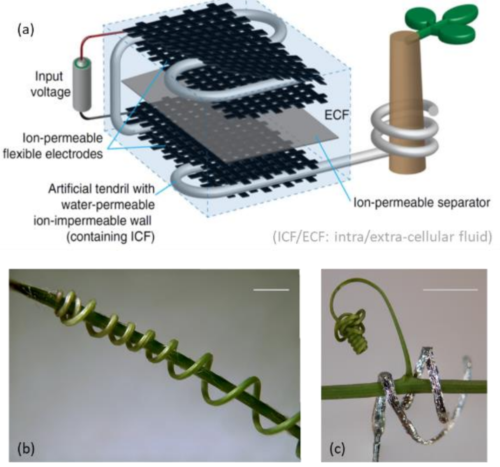

Fig. 2. (a) Reversible osmotic actuation: schematic. Voltage application causes ions in the liquid region outside the tendril to be immolized on the electrodes surface, thus inducing water flux toward the inner tendril volume, whence uncoiling and stiffening. Shortcircuit induces the reverse dynamics (b) *Passiflora caerulea* tendril anchoring to an external support. (c) Soft tendril coiling (two image overlay) around an external support. Scalebars: 5mm (more details in [4])

III. ELUCIDATING OSMOSIS-DRIVEN TURGOR FORMATION

The actuation timescale of the osmotic actuator introduced in [2] matched that one of an ideal, giant plant cell with the same typical size as the actuator. We could thus exploit the actuator to better elucidate osmosis-driven turgor formation in natural plant cells. More in detail, considering that previous studies had correlated turgor modulation to potassium chloride (KCl), although the latter not being efficiently retained in the cell, and observing that many other compounds, including L-glutamine (L-Gln) and D-glucose (D-Glc), are present in the cytosol, in [3] we demonstrated that osmolyte complexes, rather than KCl alone, are at the base of turgor formation. Our investigation also suggested the possibility of developing osmotic actuators exploiting a dynamically varying concentration of osmolytes.

IV. REVERSIBLE OSMOTIC ACTUATION

The dynamics of the osmotic actuator introduced in [2] was dictated by the initial solute concentration (i.e., NaCl in the actuation chamber, see fig.1). As suggested by (2), actuation could advance until the increased pressure difference (Δp) equaled the decreased osmotic pressure difference, as caused by water flux towards the actuation chamber. Hence, reversibility was still an open issue hampering implementation. In [4] we overcame this issue by introducing a reversible osmotic actuation strategy based on the electrosorption of ions on flexible porous carbon electrodes (Fig. 2) driven at low input voltages (1.3 V). Considering the potential of soft robots for safe interaction with delicate objects, humans and unstructured environments, yet at the same time the challenge for effectively controlling their movement and stiffness modulation, we combined the as devised actuation strategy with a soft effector. Specifically, we showed reversible stiffening (~5-fold increase) and actuation (~500 deg rotation) of a tendril-like soft robot (diameter ~1 mm). Although targeting reversible osmotic actuation (for artificial systems) *per se*, [4] further highlighted the potential of taking inspiration from the Plant Kingdom, for developing soft robots based on biocompatible materials and safe voltages making them appealing for prospective applications.

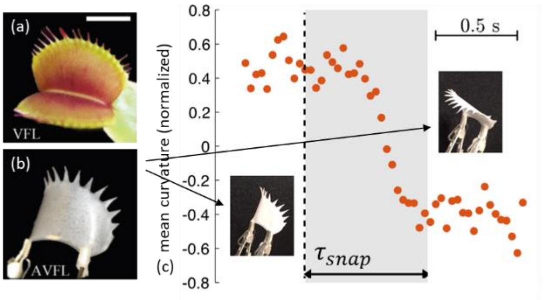

Fig. 3. Venus Flytrap leaf: (a) natural, (b) artificial. (c) Fast curvature change of the bistable artificial leaf, caused by a step humidity change (more details in [5])

V. FASTER ACTUATION THROUGH MECHANICAL INSTABILITY

Plant tissue adaptively response to environmental stimuli. Complex movements such as, e.g., twisting and coiling also exploits anisotropic swelling. Plant rapid movements, which are not bound to osmosis-driven water transport only, also involve biomechanical instabilities. In this regard, the fast closure of the Venus flytrap (*Dionaea muscipula*) provides a remarkable example, which inspired our investigation in [5], concerning hygroscopic bistable structures obtained by electrospinning (specifically, PEO nanofibers on PDMS). Given a step humidity variation, we studied both the quasistatic bending response of monostable bilayers (timescale around 10 s) and the subsequent snap-through response (timescale below 1 s) of bistable structures obtained by combining two prestretched layers (Fig. 3). Besides hinting to illustrative implementation, such as curvature modulation for soft optical focusing systems, we highlighted the potential for faster actuation based on multiple physical effects.

VI. CONCLUDING REMARKS

Following a bioinspired approach, we concurrently addressed and solved design and material issues. Plants offer an outstanding source of inspiration for developing innovative biorobotics systems, based on the synergistic integration of structural and multifunctional material properties.

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