Honeycomb Actuators Inspired by the Unfolding of Ice Plant Seed Capsules

Abstract

Plant hydro-actuated systems provide a rich source of inspiration for designing autonomously morphing devices. One such example, the pentagonal ice plant seed capsule, achieves complex mechanical actuation which is critically dependent on its hierarchical organization. The functional core of this actuation system involves the controlled expansion of a highly swellable cellulosic layer, which is surrounded by a non-swellable honeycomb framework. In this work, we extract the design principles behind the unfolding of the ice plant seed capsules, and use two different approaches to develop autonomously deforming honeycomb devices as a proof of concept. By combining swelling experiments with analytical and finite element modelling, we elucidate the role of each design parameter on the actuation of the prototypes. Through these approaches, we demonstrate potential pathways to design/develop/construct autonomously morphing systems by tailoring and amplifying the initial material's response to external stimuli through simple geometric design of the system at two different length scales.

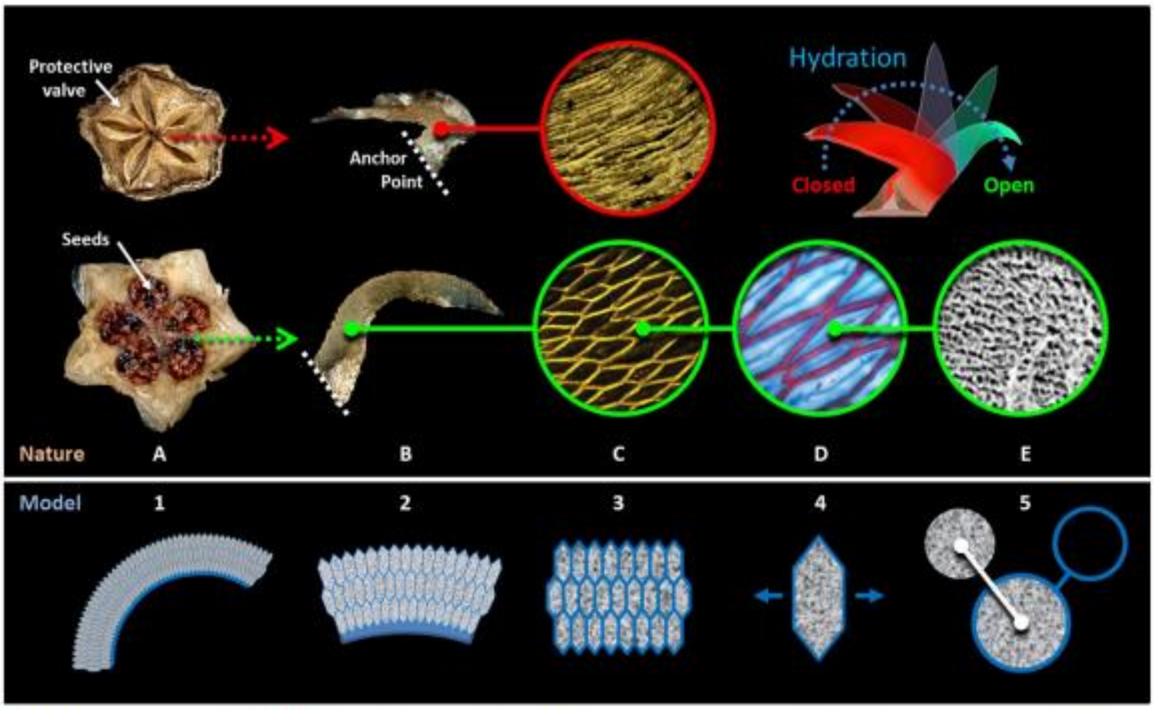

Fig 1. Ice plant hydro-actuation mechanism. Top: (A) The seed capsules of the ice plant, *Delosperma nakurense* are shown in dry (closed) and wet (open) state. The five seed containing compartments are closed and covered by a protective valve (each measuring ca. 3mm in length) in the dry state and open upon wetting. (B) Two hygroscopic keels halves responsible for unfolding/folding of the seed capsule; the keels are bent inward in the dry state and bend outward upon hydration. (C) Each keel consists of a network of ellipsoid/hexagonal shape cells (confocal microscopy images of the transverse cell cross-section -field diameter: ca. 0.4 mm). (D) A highly swellable cellulosic inner layer filling up the lumen of the cells is responsible for the unidirectional opening of the cells and the reversible anisotropic expansion/contraction of the cell-network upon wetting/drying cycles (FCA stained cells cross section with lignified cell wall stained in red and the cellulosic inner layer in blue- field diameter: ca. 100 µm). (E) Cryo-SEM micrograph of the cellulosic inner layer (field diameter: ca. 20µm). (redrawn after [8, 20]). Bottom: Abstraction of the actuation principles from lower to higher lengthscale; (5) volume change of a highly swellable material inside a circular confinement induces an isotropic volume change of the cell; (4) Tailoring the geometry of such cell enables an anisotropic deformation upon swelling/shrinkage cycles; (3) Through periodic arrangement of the cells, the cooperative anisotropic deformation of individual cells results in a unidirectional expansion/contraction of the cellular structure at a larger length scale,(2,1) which can be translated into bending of the whole honeycomb structure when the deformation is restricted at one side (re-sketched after [20]).