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Design of plant-inspired shape-changing interfaces: a review

Key words: Shape-changing interfaces; Tangible interfaces; Botanical bionics; Human–computer interaction; Smart materials

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Background

- **What are shape-changing interfaces?**
  Tangible and interactive devices that use physical changes of shape as input or output to convey information.

- **Why learn from plants?**
  Plants are natural experts in shape-changing, efficiently adapting their form to the environment.

- **Motivation: Bridging the gap**
  A persistent challenge is how to systematically translate the biomimetic principles of plants into the practical development of shape-changing interfaces. Our goal is to provide a systematic framework from biological principles to design strategies and applications.

Graphical abstract

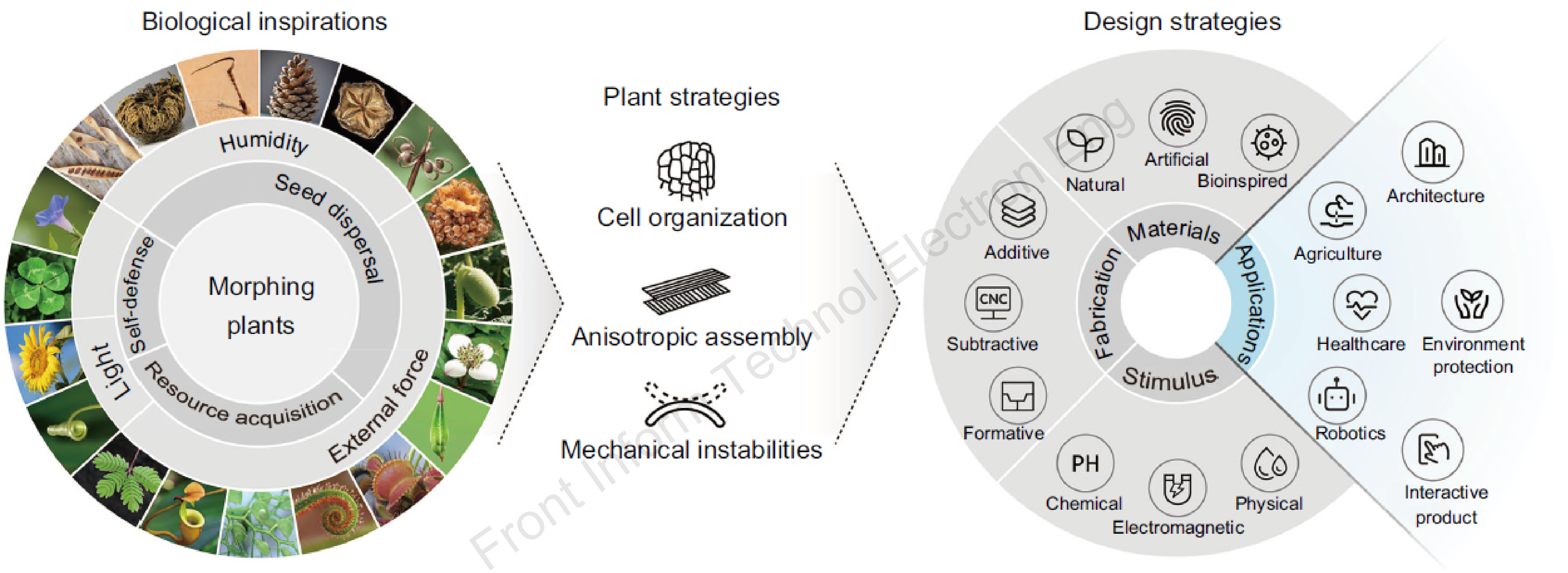
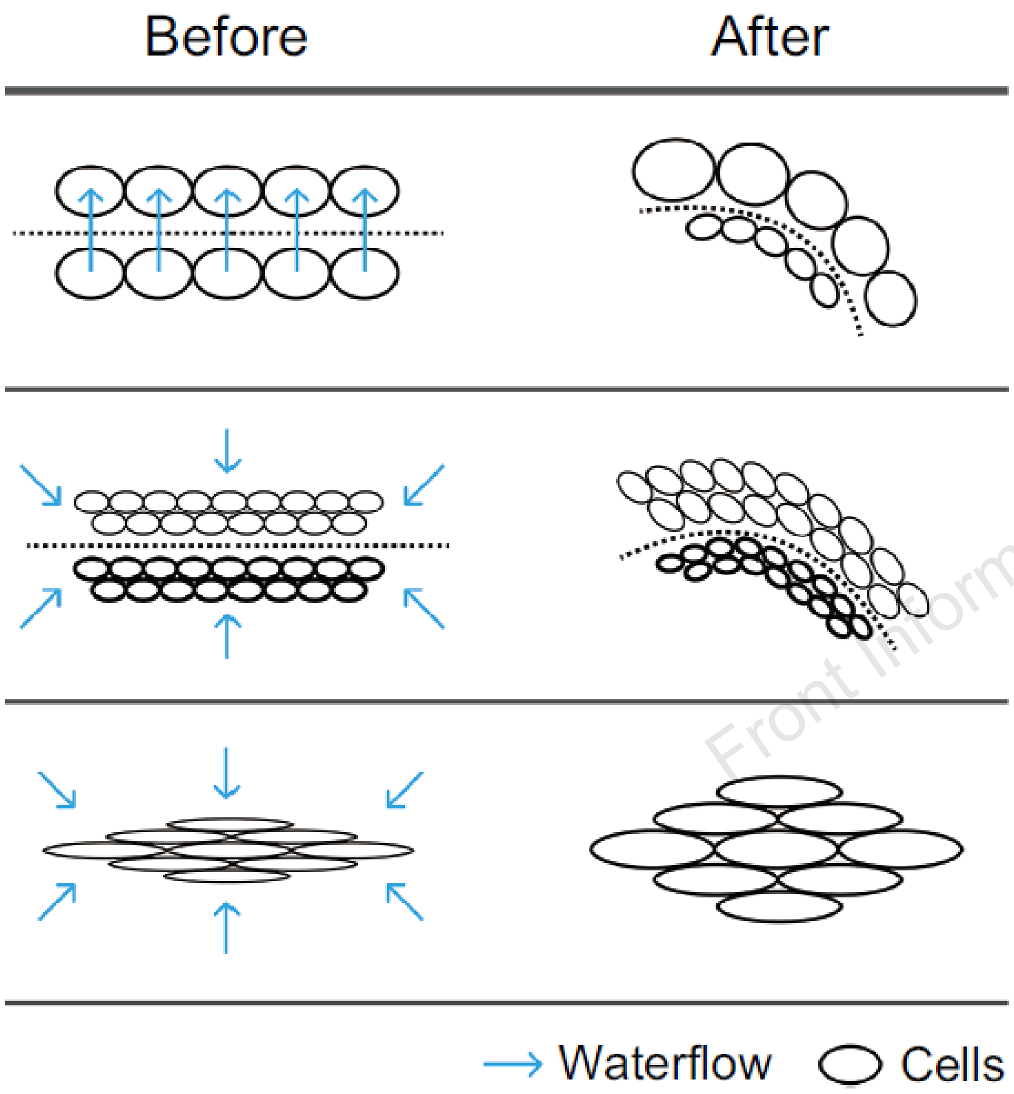


Fig. 1 A bioinspired design framework. Biological inspirations are derived from morphing plants and their adaptive strategies (cell organization, anisotropic assembly, and mechanical instabilities) to environmental stimuli (humidity/light/external force). The primary purposes of these plant deformations include self-defense, resource acquisition, and seed dispersal. Design strategies are categorized into material systems (natural/artificial/bioinspired), fabrication methods (additive/subtractive/formative), and stimulus (physical/chemical/electromagnetic). Applications span agriculture, healthcare, architecture, robotics, environmental protection, and interactive product

Shape-changing principles: Physiological features

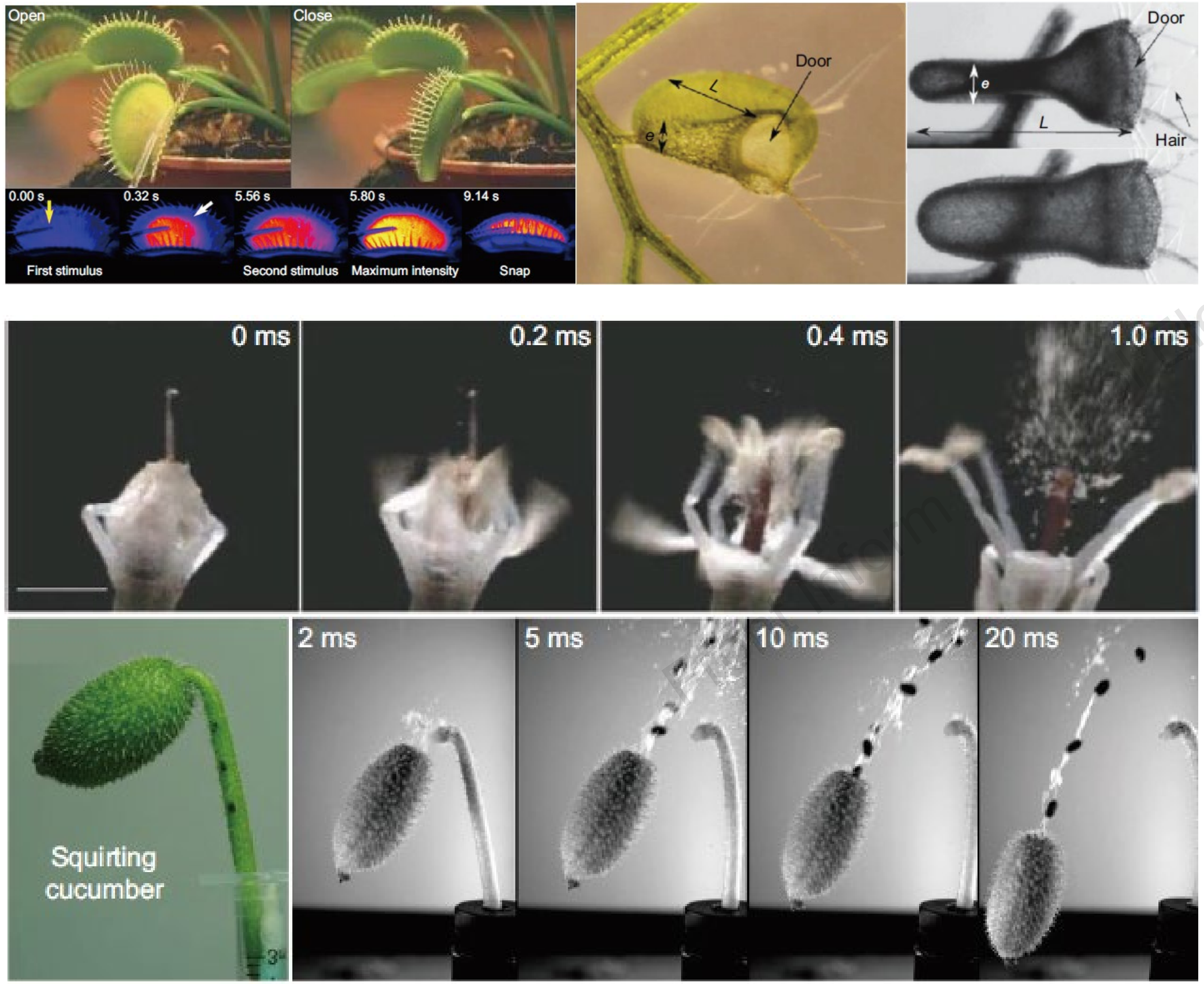


- **Cellular volume changes**
  Cellular volume changes are driven by osmotic pressure, leading to localized expansion or contraction of cells. This asymmetry generates bending forces that cause large-scale movements, such as the opening and closing of leaves in legumes.

- **Cell wall thickness differences**
  Differences in cell wall thickness and stiffness create mechanical asymmetry within tissues. When hydrated, softer layers expand more than rigid ones, leading to controlled bending or curling, as seen in resurrection plants adapting to drought.

- **Cellular origami-like structure**
  Inflation and explosion of plants can generate plenty of energy in a very short time, which provides inspirations for energy storage and release.

Shape-changing principles: Mechanical instability



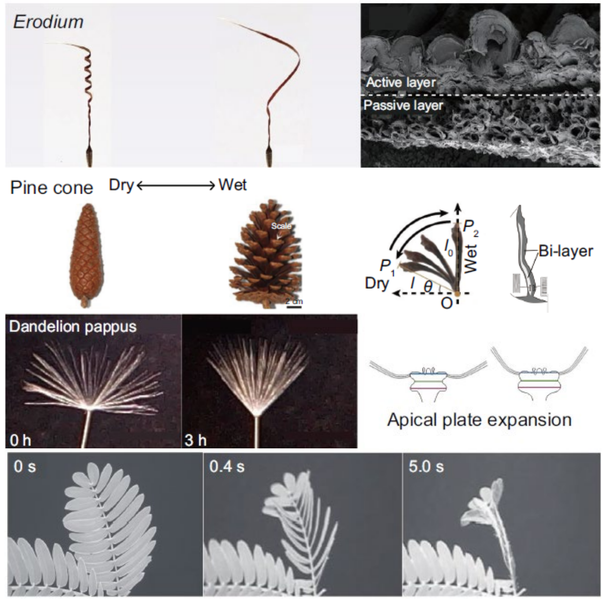
Bistability

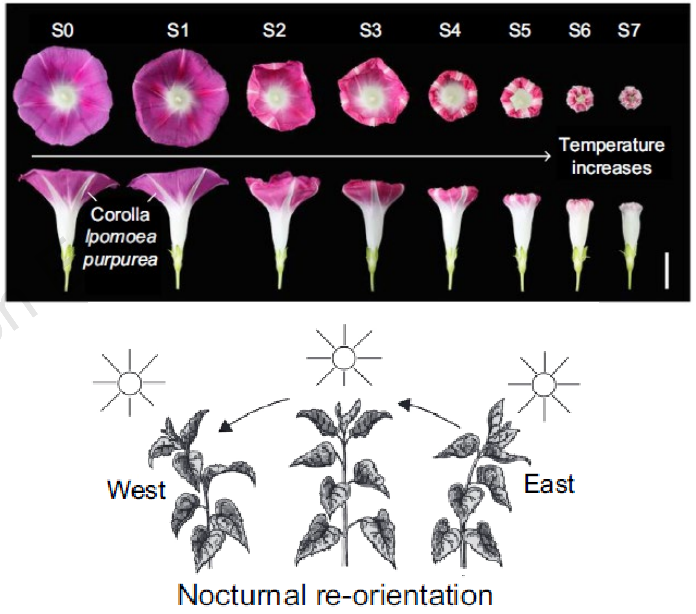
Bistability refers to the rapid and reversible switching between two stable states of a system, often triggered by external stimuli.
In plants, this mechanism is exemplified by the Venus flytrap, which snaps shut in about 0.3 s when sensory hairs are touched, and by bladderwort traps, which suddenly open under negative pressure to capture prey.

Fracturing

Fracturing involves localized structural rupture that releases stored elastic potential energy.
This principle drives high-speed dispersal events, such as the explosive pollen release in bunchberry flowers or seed ejection in touch-me-not (*Impatiens*) and squirting cucumber (*Ecballium elaterium*), where stored tension is suddenly unleashed to propel reproductive units.

Shape-changing stimuli





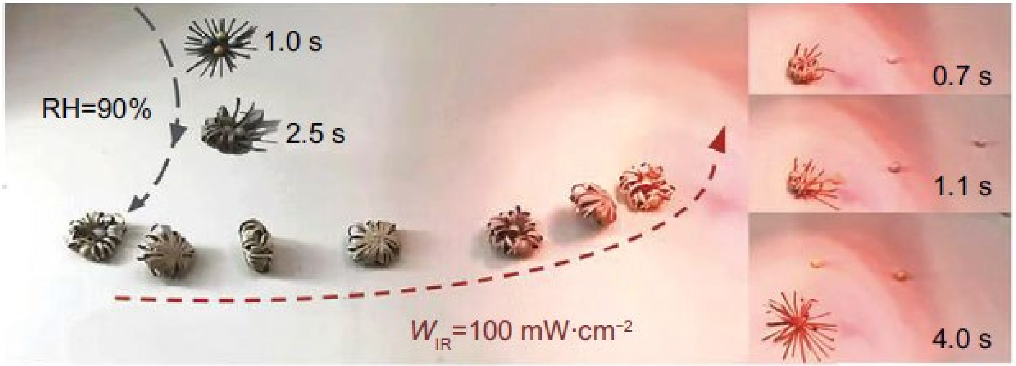
- **Humidity**
  Humidity changes cause cells or tissues to swell or shrink, driving reversible deformations such as pine cone opening or seed awn twisting.

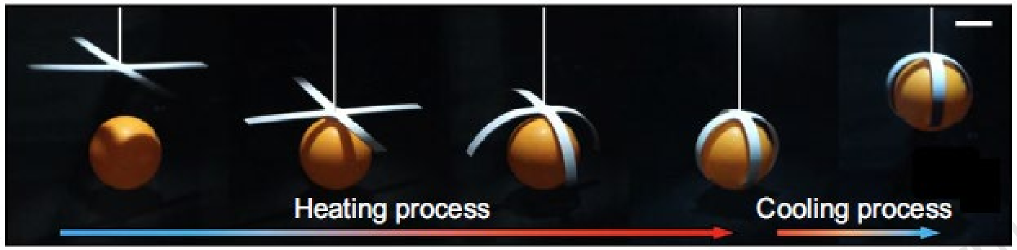
- **External force**
  Mechanical stimuli, such as touch or pressure, induce rapid movements through sudden turgor loss or structural instability, exemplified by the folding leaves of *Mimosa pudica*.

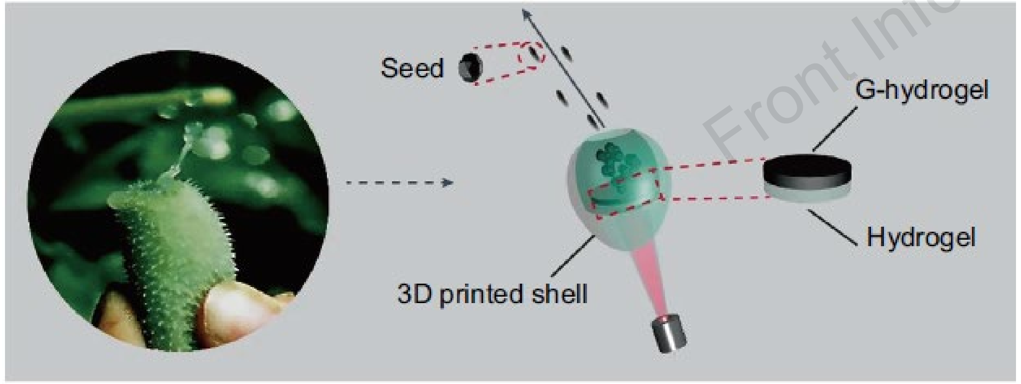
- **Temperature**
  Temperature fluctuations trigger thermonastic movements, like the daily opening and closing of morning glory flowers, helping regulate reproduction and protection.

- **Light**
  Light-driven growth responses (phototropism) guide directional movement, as in sunflowers reorienting their heads to track the sun.

Design based on shape-changing bahaviors





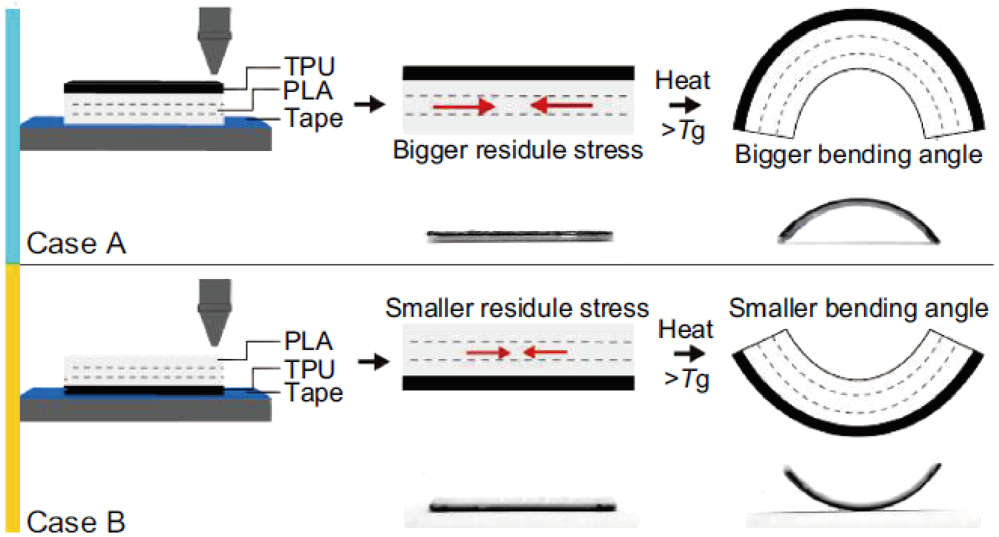


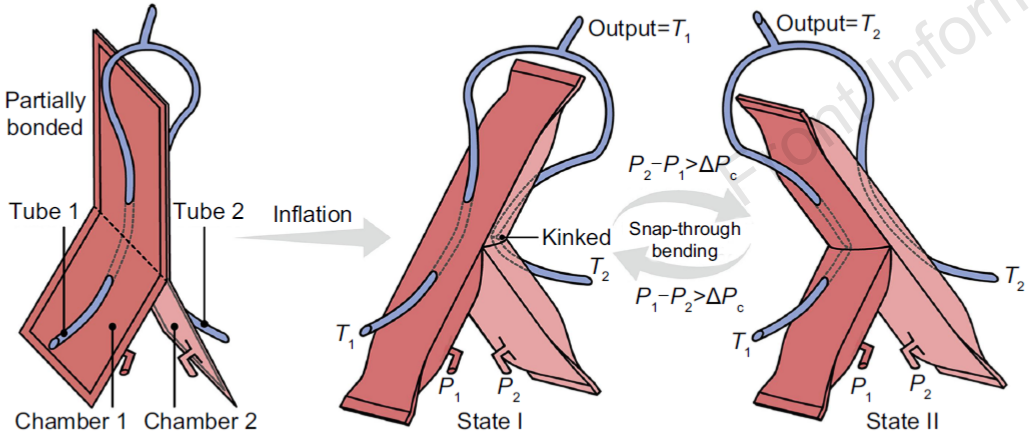
- **Growth and movement**
  Plants can grow and move in challenging surroundings adaptively, which inspires strategies for designing shape-changing interfaces to move in complex scenarios without extra power as input.

- **Bending and curling**
  Bending and curling are the simplest and most common shape-changing behaviors that researchers have learned from for multiple purposes including gripping, assembling, and cell transportation.

- **Inflation and explosion**
  Inflation and explosion of plants can generate plenty of energy in a very short time, which provides inspirations for energy storage and release.

Design based on shape-changing principles

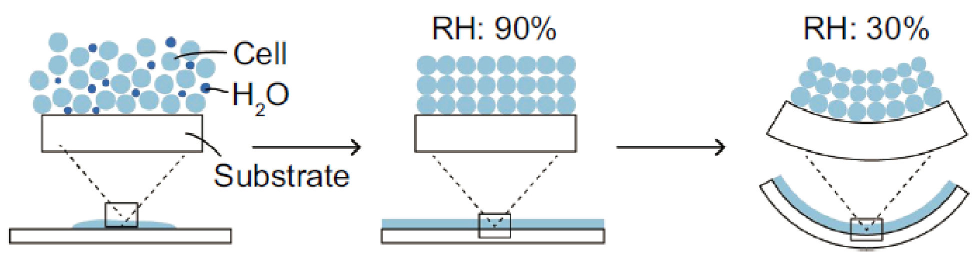


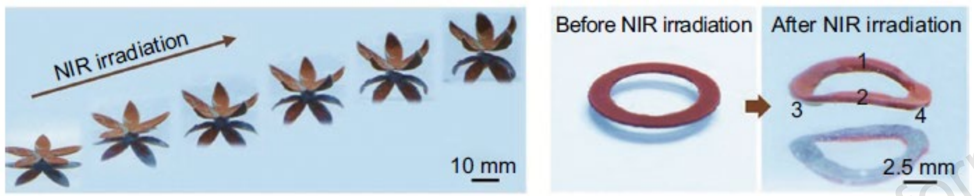


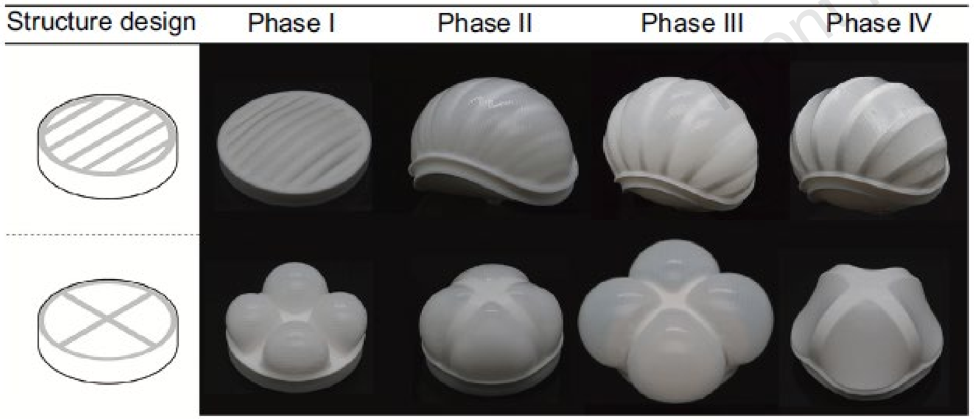
- **Design strategies inspired by bi-layer anisotropic assembly:** The anisotropic assembly of cellulose inspires the bi-layer or multi-layer structure design with material anisotropy for shape-changing in a specific direction.

- **Design strategies inspired by mechanical instabilities:** The mechanical instabilities of plants inspire researchers to combine special material properties with mechanical and logic designs.

Design strategies of stimuli





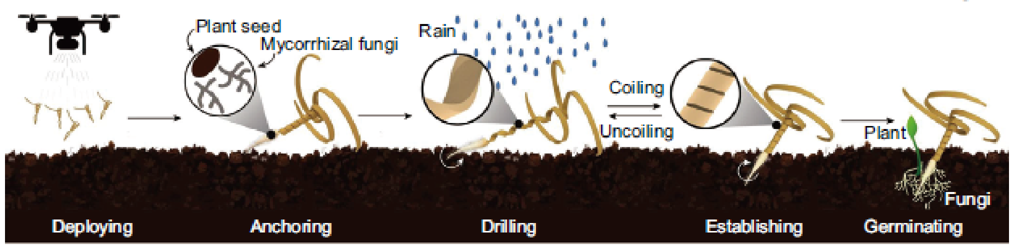


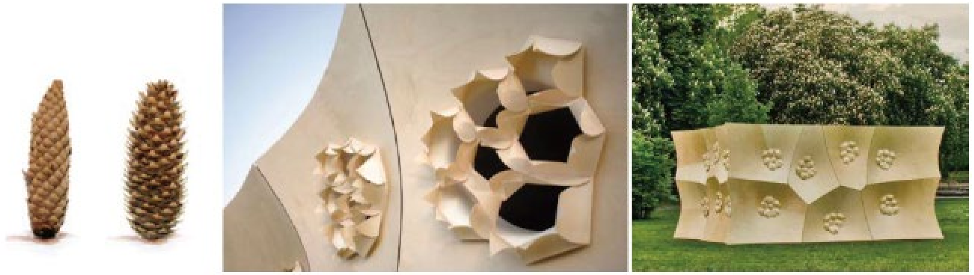
- **Humidity-response shape-changing**
  As the most common stimulus for plant systems, humidity plays an important role in shape-changing interfaces. It has been explored as the main stimulus for achieving agricultural and biomedical purposes due to its accessibility and harmlessness.

- **Light-response shape-changing**
  Light as a stimulus has raised more and more interest in shape-changing interfaces due to its rapid switching, accurate focusing, and sustainable properties.

- **Shape-changing driven by external force**
  External force indicates that the resource of the actuation comes from users' behavior rather than the environment. The most prevalent approaches include pneumatic, magnetic, and electric actuation.

Applications





- **Agriculture**
  - Precision irrigation inspired by *Ficus religiosa* leaves
  - Self-burying seed carriers inspired by *Erodium* seeds
  - Humidity-driven micro-cargo transport inspired by *Avena* fruit
- **Healthcare and rehabilitation**
  - Adaptive orthoses inspired by climbing plants
  - Venus flytrap snap mechanism
  - TransfOrigami system inspired by *Oxalis*
- **Architecture**
  - Sunflower-inspired facades
  - Pine cone-inspired humidity facades

Applications

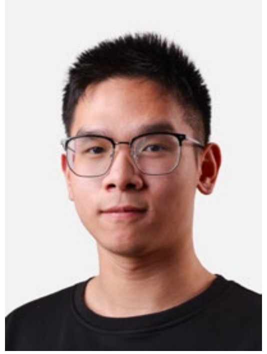
- **Robotics**
  - Climbing plant-inspired robots
  - *Pelargonium carnosum*-inspired microrobot
- **Environmental protection**
  - Sunflower-inspired wearable device
  - Environmental sensors
  - Seed dispersal strategies
- **Interactive products**
  - Touch-reactive devices inspired by *Mimosa pudica*
  - 3D-printed cactus spines & dandelion seed fluff

Challenges and opportunities

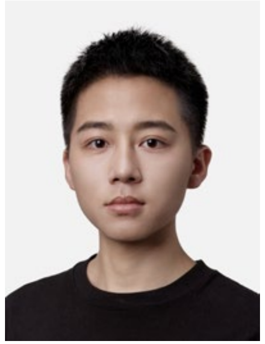
Focus	Challenges	Opportunities
Interdisciplinary design thinking	Cross-domain knowledge; hard translation	Shared vocabulary; collaborative tools
Dynamic behavior	Descriptive, trial-and-error; no predictive models	Physical theories; computational models
Material choice	Performance vs. sustainability; durability	Programmable, bio-based, sustainable materials
Fabrication process	Customization vs. scalability; reproducibility	AI-assisted, modular toolkits
Energy integration	Fluctuating natural sources; complex integration	Embedded harvesting; hybrid systems; low-power control
Function–scenario matching	Diverse requirements; difficult alignment	Adaptive, cross-domain frameworks
Large-scale deployment	Mass production vs. customization; quality	Balanced, scalable manufacturing
Performance and reliability	Uncertain long-term stability	Standardized tests; adaptive mechanisms
Policy, ethics, and regulation	No regulation; safety, liability issues	Balanced policies; responsible innovation

Author bio

Junzhe JI is now a Ph.D. student at the College of Computer Science and Technology, Zhejiang University. His research interests focus on human–computer interaction, digital design and manufacturing, and intelligent sensing.



Chuang CHEN is now a master's student at the Polytechnic Institute of Zhejiang University. His research interests focus on human–computer interaction, tangible interface interaction, and bionic deformation design.



Boyu FENG is now a Ph.D. student at the College of Computer Science and Technology, Zhejiang University. His research interests focus on intelligent material systems, tangible human–computer interaction, digital design and fabrication, and plant-inspired bionic design.

Author bio

Ye TAO is an associate professor and deputy director of the Industrial Design Department of Zhejiang University City College. She also serves as a part-time expert at the International Design Institute of Zhejiang University, and is an executive member of the Computer-Aided Design and Graphics Committee and the Human–Computer Interaction Committee of the China Computer Federation. She mainly works on designing and fabricating shape-changing interfaces, and digital craft.

Guanyun WANG is a tenure-track professor and associate head of the Department of Industrial Design at Zhejiang University. His research revolves around design and fabrication. His works have been published and exhibited across science, engineering, design, and art. He has published papers in top journals and academic conferences such as *Nature*, *Science Advances*, CHI, UIST, and UbiComp.