Plant-inspired robotics for environmental sustainability

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A mutual benefit: science and technology

"Let Nature be your teacher" [William Wordsworth]

"Take and Give back" Philosophy
Robotics and Artificial Intelligence have progressed enormously
Abilities that robots have not reached yet

Lessons from Nature
Simplifying principles for a complex world
Adaptation as a form of intelligence
Morphological computation: A modern perspective on intelligence

The shape as body structure, specifies the behavioral response of the agent.

The arrangement of the motor, perceptive and processing units.

The mechanical properties allow emergent behaviors and highly adaptive interaction with the environment.

Zambrano, Cianchetti and Laschi (2014); Pfeifer and Bongard (2007); Paul (2006)
Plants: an exceptional example of brainless distributed intelligent systems
<table>
<thead>
<tr>
<th><strong>Animals</strong></th>
<th><strong>Plants</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Non modular organization</td>
<td>Modular organization</td>
</tr>
<tr>
<td>Determinate growth</td>
<td>Indeterminate growth</td>
</tr>
<tr>
<td>Movement by locomotion</td>
<td>Movement by growth</td>
</tr>
</tbody>
</table>

There are likely advantages for developmentally mimicking plants
The first robot inspired by plants as pioneering worldwide research for Growing Robotics
The role of growth in plants
Root penetration strategy

**MATURE ROOT:**
- Stationary conditions
- Lateral hairs development

**ELONGATION ZONE:**
- Cell elongation
- Pressure up to 1 MPa

**ROOT CAP**
- Border cell sloughing
- Mucilage production

**MERISTEMATIC REGION**
- Cell division

**ANCHORAGE**

**GROWTH FROM THE TIP**

**DECREASING FRICTION**
Moving by growing

Plant-inspired self-growing robots

The robot grows by deposition of thermoplastic material

Sadeghi et al. (2017) *Soft Robotics*; Del Dottore et al. (2018) *ICRA*
Plant-inspired self-growing robots

Robotic root growth in air

Robotic root growing in an artificial soil

Sadeghi et al. (2017) Soft Robotics
EFT is more efficient
Faster Penetration (+40%)
Lower Power (-70%)
Sadeghi et al. (2014) PloS One
Passive morphological adaptation

Sadeghi et al. (2019) Soft Robotics
Movement and adaptation by stiffness variation
Stiffness generated by water flux

Turgor pressure generated by osmosis

\[ \Delta \Pi = \Pi_0 - \Pi_i \]

(_guard cells)
Plants use a wide variety of low-power-consumption osmosis-based movements

A new class of high-efficiency and low-power-consumption forward osmosis-based actuators

The role of osmosis in plants

Exemplificative “macroscopic” actuation tasks

FASTER MOVEMENTS
The actuator can trigger a preloaded mechanism

SLOWER MOVEMENTS
The actuator can raise a 2 kg beam (20mm² membrane surface)
Reversible anchoring by osmotic actuation

A variable-stiffness tendril-like soft robot based on reversible osmotic actuation

polyethylene terephthalate (PET) tube

Main components of the soft robot

Must, Sinibaldi, Mazzolai (2019) Nature Communications
Soft tendril-like arms

- 5-fold increase in bending stiffness (EI=0.3 to 1.5 N/mm²)
  in 25 min (timescale comparable to natural tendrils)
- 1.3 V source
- Tip rotation: 500 deg in 26.5 min

Must, Sinibaldi, Mazzolai (2019) Nature Communications
The role of intrinsic structural properties
Bistability in Nature Venus flytrap (Dionaea)

Microscopic investigation

- upper epidermis
- microfibrils
- lower epidermis
- mesophyll
- upper epidermis
A Plant-inspired Soft Bistable Structures

Silanization of a silicon wafer

PDMS substrate by spin coating deposition

Bistable Sheet (BS)

Unixial pre-stretch

Hygroscopic BiLayer (HBL)

Hygroscopic Bistable Structure (HBS)

Electrospun Polyethylene Oxide (PEO)

Hygroscopic Nanofibers

Lunni et al. (2020) Advanced Material Interfaces
A Plant-inspired Soft Bistable Structures

Conceptual design

1. RH₁
2. RH₂ > RH₁

passive substrate (lower epidermis)
hygroscopic material (upper epidermis)

Natural structure

Artificial structure

Lunni et al. (2020) Advanced Material Interfaces
A Plant-inspired Soft Bistable Structures

Lunni et al. (2020) Advanced Material Interfaces
PDMS Lens on the HBS for light focusing

Figure 3 (a) HBL in dry and moist environment (scale bar: 1 cm). (b) HBL schematic used for modeling water diffusion. (c) MaterialsViews.com 2015 by Chemie Gesellschaft mbH. Schematic pattern of layer (SEM): PS onow sorption (ii) cutting of the current PEDOT position due to the PEDOT (SEM) (iii) sorption/desorption due to the PEDOT content (left). PS onow sorption (ii) cutting of the current PEDOT position due to the PEDOT (SEM) (iii) sorption/desorption due to the PEDOT content (left).
The role of passive movements in plants
Movements without muscles
Responsive materials

Plant-inspired hygromorphic actuators

Responsive materials

Plant-inspired hygromorphic actuators

Passive Actuation
(Driven by environmental humidity)

Current-based Actuation
(Driven by Joule Heating)

Towards new frontiers for distributed environmental monitoring based on an ecosystem of plant seed-like soft robots
I-Seed scenario

- **Onboard data-driven flight & data georeferencing software**
- **Mathematical model-guided design for flight and penetration**
- **Biodegradable seed-like soft robots**
- **I-SeedSam** humidity, temperature, $CO_2$ in air above the top soil
- **I-SeedEro** humidity, temperature, $Hg^{2+}$ in the top soil
- **Distribution models, environmental data management and validation**
- **Drone with fLiDAR**
GROWBOT

The first robot inspired by climbing plants able to anchor and negotiate voids
The role of morphology
Hook-Climbers (*Galium aparine* L.)

Fiorello et al. (2018) Conference on Biomimetic and Biohybrid Systems
Hook-Climbers (*Galium aparine L.*)

-Fiorello et al. (2018) Conference on Biomimetic and Biohybrid Systems
Hook-Climbers (*Galium aparine* L.)

**Attachment test of single hook**

**Specimens**
- Natural AB
- Artificial AB
- Natural AD
- Artificial AD

**Setup**
- Load cell
- Portable microscope
- Customized support

**Test**

Fiorello et al. (2020) *Advanced Functional Materials*
Mini car with plant-inspired wheels

Adhesive tape with direction based-microhooks

Fiorello et al. (2020) *Advanced Functional Materials*
<table>
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<tr>
<th>Artificial skin tissue</th>
<th>Polyester tissue</th>
<th>Loop part (Velcro)</th>
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<tbody>
<tr>
<td><strong>Without hooks</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>![Image 1]</td>
<td>![Image 2]</td>
<td>![Image 3]</td>
</tr>
<tr>
<td><strong>With hooks</strong></td>
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<td></td>
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Plant materials as energy harvesting source
Bio-hybrid energy source: In vivo energy conversion at the plant leaf cuticle

The structure of plant leaves resembles triboelectric generators that convert mechanical into electrical energy...

Bio-hybrid energy source: In vivo energy conversion at the plant leaf cuticle

... which can be harvested...

Bio-hybrid energy source: In vivo energy conversion at the plant leaf cuticle

Bio-hybrid energy source: In vivo energy conversion at the plant leaf cuticle

... and used as bio-hybrid power source

Rhododendron leaf generates ~15 µW/cm² leaf surface when touched by Ecoflex at 1 N impact force.

100 LEDs powered by a single R. leaf

Bio-hybrid energy source: In vivo energy conversion at the plant leaf cuticle

*Nerium oleander*-hybrid harvesting wind energy

Meder et al. (2018) *Advanced Functional Materials*; F. Meder et al. (2020) *Energy Technology*
New frontiers: remote areas in-situ monitoring

Mobile robots with embedded sensors
Meghalaya, India
Forest Intelligence: Robotic Networks inspired by the Wood Wide Web
Forest Intelligence:
Robotic Networks inspired by the Wood Wide Web

Source: BBC
The history of Plant-inspired Robotics and European Vision

- 2007: SeedBot
- 2008: Electro-osmotic actuation
- 2012: Plantoid
- 2013: Sloughing mechanism
- 2014: Growing proof of concept
- 2014: SeedDriller
- 2017: EOLO
- 2017: 3D printer growing
- 2018: SMASH
- 2018: Energy from plants
- 2019: GrowBot
- 2019: Tendril-like robot
- 2021: I-Wood
- 2021: I-Seed
- 2021: I-Seed
What do we need?

To break the walls among the disciplines

To train young researchers and students to face interdisciplinary problems and curiosity-driven research

Bioinspired robotics can balance modern scientific fragmentation and promote the growth of a new generation of inventors and entrepreneurs!
Robots that help increase the planet resources, instead of just exploiting them.

Mazzolai and Laschi (2020) *Science Robotics*
Acknowledgements

Thank you!

Never be limited by other people’s limited imagination

Mae Jemison
(American astronaut and physician)

Thank you!
Acknowledgements for funding

Thank You!