NOVEL SENSOR TECHNOLOGIES FOR PLANT PHENOTYPING

SMART TECHNOLOGICAL SOLUTIONS INSPIRED FROM BEHAVIOUR AND ADAPTIVE STRATEGIES IN PLANTS

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Dr. Schmitt and his wife completed an incredible dual career studying natural biological processes and inventing methods and machines that duplicated those actions. This new science became known as "Biomimetics" or "The Mimicry of Nature."

His doctoral research was an attempt to produce a physical device that explicitly mimicked the electrical action of a nerve.

The word *biomimetics* was used for the first time by Schmitt on 1957. Later, Schmitt used the word biomimetics in the title of a paper (Schmitt, O. 1969 Some interesting and useful biomimetic transforms. In Third Int. Biophysics Congress, p. 297)
Chinese tried to make an artificial silk more than 3000 years

Leonardo da Vinci studied bird flight and designed some machines
Biorobotics Science: using robotics to *discover new principles* ...

Biorobotics Engineering: using robotics to *invent new solutions* ...

(Paolo Dario, Scuola Superiore Sant’Anna, Pisa, Italy)

... either inspired by biological models, and aimed at generic applications ... ... or simply applied to biological models

Courtesy of M. Brega
To identify the biological system(s) responsible for producing the desired characteristic

To extract the key principles underlying their biological function

To translate them to a technological solution

Consequently, one cannot simply copy Nature, but rather carefully choose Nature’s behaviour of focus, and extract the underlying principle at a level of description that is actually possible to implement.
BIОINSPIRED PRINCIPLES AND TECHNOLOGIES FOR ARTIFICIAL EXPLORATION
WHY A ROBOT MUST BE INSPIRED BY PLANTS?
PLANTS AS PASSIVE ORGANISMS

• No **movement**, in an animal meaning
• No **communication** with other plants or organisms
• No **possibilities to escape** from a hostile environment
NEW VISION OF THE PLANT’S WORLD

Plants demonstrate to successfully reach their needs even without a conventional locomotion system. They have developed growth response to deal with the copious and rapid changes in their environment. These responses are known as tropisms. The directional growth of plant organs in response to a directional environmental stimulus:

- **Phototropism**: Light
- **Gravitropism**: Gravity
- **Thigmotropism**: Touch
- **Hydrotropism**: Water
- **Chemotropism**: Chemical

A young bean moves around to sense structures to be used as support.

*Videos courtesy of Stefano Mancuso (UNIFI)*

A primary root follows the gravity \(2.7 \cdot 10^{-4} \times (1s = 1h)\)
Lessons from plant tissue in complex actuation by swelling – Example of actuator systems inspired by plants that are able to move as a result of water absorption and based on hygromorphic principles.

I. Burgert and P. Fratzl “Actuation systems in plants as prototypes for bioinspired devices”, Phil. Trans. R. Soc. A 367, 1541-1557, 2009

**Actuation Mechanism in Pine Cone**

**Swelling and shrinking of matrix polymers**

Orientation of cellulose microfibrils in the scales of the pine cone.

**Multifunctional Materials**

**Hierarchical Architectural Structures**

**Integrated Design**

**Adaptive Behaviour**

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**Swelling and shrinking of matrix polymers**

- Orientation of cellulose microfibrils in the scales of the pine cone.

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**Actuation systems in plants as prototypes for bioinspired devices**, Phil. Trans. R. Soc. A 367, 1541-1557, 2009

Active Actuation in Plants: Venus Flytrap

Video courtesy of Stefano Mancuso (UNIFI)

Venus flytrap (*Dionaea muscipula*)

*(about 1s to close completely but only about 100 ms to “trap”)*

This mechanism relies on geometrical and materials anisotropy as well as heterogeneity, turgor pressure and action potentials

I. Burgert and P. Fratzl “Actuation systems in plants as prototypes for bioinspired devices”, Phil. Trans. R. Soc. A 367, 1541-1557, 2009
WHY PLANTS? (FOR A ROBOTICIST)

Rich sensing and coordination capabilities

Adaptive growth and behaviour

Energy-efficient actuation and high sustainability

Redundancy

Plant’s World
What makes for much greater complexity is that many of these signals arrive coincidentally. Decisions among often conflicting signals have to be made and priorities determined on phenotypic change. This enormous complexity of signalling ensures that no plant behavioural response is autonomic.
“the (root) tip... acts like the brain of one of the lower animals; the brain being seated within the anterior end of the body, receiving impressions from the sense organs, and directing the several movements”.

**Charles Darwin and Francis Darwin (1880)**

**The power of movements in plants. John Murray, London**
**WHY PLANT ROOTS? (FOR A ROBOTICIST)**

From the biological viewpoint to the robotics perspective: what are the plant’s behavior and mechanisms that we want to imitate?

<table>
<thead>
<tr>
<th>Actuation system</th>
<th>Sensory system</th>
<th>Kinematics</th>
<th>Emergent behavior</th>
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<td>Osmotic –based process</td>
<td>Plants sensors</td>
<td>Elongation from tip</td>
<td>Roots move in a responsive way</td>
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<td>- Ions, ...</td>
<td>- Penetration</td>
<td>- Kin selection, ...</td>
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- Emergent behaviour
  - Exploration /Penetration tasks
  - Rich sensing
  - Emergent behaviour
  - Energy-efficient actuation
  - Coordination capabilities

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**Why Plant Roots**

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**Energy-efficient actuation**

**Exploration/Penetration tasks**

**Coordination capabilities**

**Rich sensing**

**Emergent behaviour**
**The Osmotic Principle as Actuation Strategy**

* Mimosa pudica
* Videos courtesy of Stefano Mancuso (UNIFI)

* Genus Stylidium
* Cnidocysts

**The Osmotic Principle in Nature**
### Stomata's guard cells
- **Max pressure**: 4.5 MPa
- **Velocity**: -
- **Actuation time**: -
- **Characteristic dimension**: ~ 50 μm
- **Reversibility**: Yes

[A. Hetherington, Current Biology, 2001]

### Dionaea muscipula (Venus flytrap) leaf
- **Max pressure**: -
- **Velocity**: ~ 1.5 rad/s
- **Actuation time**: ~ 0.05 s
- **Characteristic dimension**: 10 – 25 mm
- **Reversibility**: Yes

[Y. Forterre et al., Nature, 2005]

### Mimosa pudica: leaves closure movement
- **Max pressure**: -
- **Velocity**: -
- **Actuation time**: ~ 2 s
- **Characteristic dimension**: <1 mm
- **Reversibility**: Yes

[M. Taya, Eapad, 2003]


### Stylidium flower: pollination movement
- **Max pressure**: -
- **Velocity**: ~150 rad/s
- **Actuation time**: 10 - 25 ms
- **Characteristic dimension**: -
- **Reversibility**: Yes

[B. S. Hill, Quarterly Reviews of Biophysics, 1981]

### Plant root apex
- **Max pressure**: ~ 1 MPa
- **Velocity**: ~ 1 mm/h
- **Actuation time**: -
- **Characteristic dimension**: ~1 mm
- **Reversibility**: No

[L. J. Clark et al., Plant and Soil, 2003]
3-cell actuator: this solution maintains the osmotic process and allows the steering mechanism in a compact and easy way.

It is possible to set the potential of electrodes two at a time or all together, changing the concentration across the three cells and generating the expected water flow.

Pistons for the actuation

Silicon membrane

Size: Diameter: 22 mm
Height: 16 mm

Metallic electrode

Grating with osmotic and anionic/cationic membranes

Water solution

Spherical joint for steering
**ACTUATION SYSTEM: FIRST PROTOTYPE**

Fabricated by rapid prototyping with an *inVision 3D Printer* and acrylic material

Apex performances:
- Piston force → 2.12 N @ 3 atm
- Actuation time → 3 atm in less than 3 hours
- Solution → lead acetate
- Difference in [ ] → 0.5 molar
- Steering → ±13°


Hydraulic pressure system for testing the steering capabilities & gravitropic/hydrotropic response

First robotic apex
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**Energy-efficient actuation**

**Coordination capabilities**

**Exploration/Penetration tasks**

**Rich sensing**

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**Why Plant Roots**

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Experimental observation of plant roots movements

**Facing questions:**
- Kinematics
- Tropism Mechanisms
- Collision detection
- Emergent behaviour

**Simplifications:**
- Terrain lack
- 2D constrained growing

**Set Up**

- HighResolution time-lapse capture
  - 12.1 megapixels
- Controllated Chambres
  - Temperature (24-25 °C)
  - Umidity (saturated)
  - Dark cell
- Seeds
  - Mais Kubrick
  - Rice
Analyzer for Root Tip Tracks: a novel image-analysis tool
Why a New Software?

Massive Automated Elaboration

Focus on Movements

General Set of Outputs

Long Period Observation

• Detection of primary and secondary roots
• No need of markers
• Non-destructive method
• No human intervention
• Tracking over time

Quantitative data:
• Trajectory
• Displacement
• Velocity
• Direction and Orientation
• Generation of root tip traces
Results


Spatial resolution of 61 μm px⁻¹ with time lapse of 20 min. Images show tip movements at intervals of 80 min.
Root Penetration Strategies

• Root Growth from the Tip
  o To avoid as much as possible frictional energy dissipation and tissue damages.

• Apex Anchorage
  o To avoid the root uplifting instead of penetration and to reduce buckling

• Circumnutational Movements
  o To find the paths with less mechanical impedance
  o To push the soil and small particles aside or to circumnavigate the particles with bigger diameter

• Frictionless Penetration
  o To avoid as much as possible frictional energy dissipation and tissue damages

• Morphological Changes
  o To optimize the interaction with soil
Root Growth from the Tip

Root Apex:

Root Apex Interaction with the Soil:

From Engineering Viewpoint:

Rootic Response

- RC = root cap
- QC = quiescent center
- TZ = transition zone
- EZ = elongation zone
- CS = control system

PLANTOID Project
Center for Micro-BioRobotics
**Anchorage is achieved by:**

- Cumulative friction and shear resistances between the soil particles and maturing tissues behind the elongation zone (Bengough et al., Plant and Soil, 1997).
  - **Diameter enlargement** during the growth enhances this effect.

- Major changes in **root trajectory** that sometimes occur in compacted soils (enabling the reaction force to be transferred to the soil matrix at the bend in the root).
  - This may occur as a consequence of bending and nutation.
CIRCUMNUTATION: WANDERING GROWTH

Importance of the nutations in roots:

- facilitate **soil exploration** by finding pathways with less soil impedance
- **anchorage** in flooded soil (Inoue et al., Ecol Res, 1999)
Nutational movements:

- pendulum *

- waving and spiraling *

* Migliaccio et al., Plant Signal Behav, 2009

1 s = 10 min

½ period 26-66 min

1 s = 20 min

• waving and spiraling period 46-110 min
CIRCUMNUTATION MOVEMENTS

- **up-down waving**
  - Period: 38-110 min
  - Wave periods and amplitudes are not correlated

- micronutations
  - 1 s = 20 min

Obstacle avoidance behaviour

Characterization of the **tip-to-barrier angle** with respect to the obstacle orientation, which occurs in 3 phases:

1) approaching to barrier
2) transient period after first contact
3) stable period during obstacle avoidance in primary and lateral roots.

Flat obstacles

Tip angle (°)

Growth and kinematics
**Preliminary results**

*What does it happen when the substrate cannot be penetrated?*

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**Force Z, N**

**Time, min**

- 1
- 31
- 61
- 91
- 121
- 151
- 181

**Contact**

Root is pushing
The low friction properties of penetrating roots:

- Mucilage lubrication 58%
- Sloughing cells smaller coeff. of friction 42%

(From Bengough et al., Plant and Soil, 1997)

**Table 2. Root growth pressure (MPa) of seminal roots as affected by decapping and mucilage treatment**

<table>
<thead>
<tr>
<th>Mucilage treatment (MT)</th>
<th>Decapping treatment (DT)</th>
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<tbody>
<tr>
<td></td>
<td>Decapping</td>
</tr>
<tr>
<td>Mucilage</td>
<td>0.288 ± 0.005</td>
</tr>
<tr>
<td>Non-mucilage</td>
<td>0.328 ± 0.029</td>
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ANOVA
- DT ***
- MT **
- DT × MT ns

Roots were grown in compact (1.5 Mg m⁻³) soil for 12 h. Mean soil mechanical impedance at 2–4 mm soil depth was 1.59 MPa. Values are the means ± s.e. of seven to nine replicates.

*** and **, Statistically significant at $P < 0.001$ and $P < 0.01$, respectively; ns, not statistically significant at $P ≥ 0.05$.

(From Iijima et al., Annals of Botany, 2004)
Morphological Changes

🌿 Morphology as a result of root-soil interaction
  • Streamline shape
  • Conical root cap

🌿 Mechanical impedance effects
  • The elongation rate decreases
  • The root diameter increases

🌿 Root shrinking & swelling

From Abdalla et al., J agric Engng Res, 1969
(From Iijima et al., New Phytol, 2003)
4 different tip profiles: conical, parabolic, catenary, and elliptical

3 tip diameters: 10 mm, 20 mm, and 30 mm (height - radius ratio 1.5)

3 height-radius ratios: 0.5, 1, and 1.5

3 diameters of glass beads: 0.04 mm, 0.5 mm, and 5 mm
Results

- Optimal profiles: conical and parabolic
- Optimal height-radius ratio: as high as possible → trade-off with bending capabilities
- Tip diameter: at least two times greater than the diameter of soil particle
- Range of optimal penetration velocity

![Graph showing the range of optimal penetration velocity.](image)

![Graph showing the force (N) vs height-radius ratio.](image)
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- Energy-efficient actuation
- Exploration/Penetration tasks
- Emergent behaviour
- Coordination capabilities
- Rich sensing
Developed model to describe Emergent Roots Behaviour:

**Growing Conditions:**
- Availability of all the required resources
- Uniform distribution of nutrients

**Growing Target:**
- Gravity
- Proximity

**Biological model**
- VEL X $3.6 \times 10^4$ (1S=10H)
- PERIOD = 170H

**Artificial model**
- 12 ROOTS
- $W_G = 0.1$ $W_F = 0.5$

To note: the main root follows predominantly vertical direction in both models


A plant-like robotic system, or *PLANTOID*, by imitating the plants strategy, should slowly move inside the ground exploring efficiently the environment (e.g. water and life-signature on Mars), and showing **high actuation forces** and **low power consumption**.

**Soil monitoring**

**Soil exploration in space**

**ARIADNA Programme by European Space Agency (ESA)**

(c) Virgilio Mattoli - CRIM Lab
THE PLANTOID PROJECT

EUROPEAN PROJECT - 7TH FRAME PROGRAMME (FP7)
ICT-2011.9.1 FET Open

Innovative Robotic Artefacts Inspired by Plant Roots for Soil Monitoring

Project Duration: 36 months
Starting Date: May 1, 2012
Coordinator: Barbara Mazzolai
IIT@SSSA

Evaluation Score 15/15
Plant roots show different solutions to assure an efficient penetration of soil. This behaviour includes movements, mechanical changes, frictionless strategies.

Movements occur thanks to the interaction of plant ultra-structured materials with changeable environmental conditions (e.g. temperature, humidity, etc.).

These actuation mechanisms and penetration strategies of plant roots will offer and represent a great source of inspiration to design and develop a new generation of actuators and intelligent robots for soil exploration.

Nevertheless, the transfer of a concept or mechanism from living to non living systems is not trivial. We need to unveil embodied intelligence of biological models to develop/deploy robotic platforms able to interact with their environments effectively, adaptively, and safely.
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+ EPPN Workshop Organizers!
Thank you!

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