SEVENTH FRAMEWORK PROGRAMME

European Plant Phenotyping Network

EPPN

September 13th – 14th , 2012 Wageningen, The Netherlands

Novel Sensor Technologies for Plant Phenotyping

Smart Technological Solutions Inspired from Behaviour and Adaptive Strategies in Plants

iit @SSSA

Center for Micro-BioRobotics@SSSA
Istituto Italiano di Tecnologia (IIT)

Barbara Mazzolai

Biomimetics: lessons from Nature

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**."

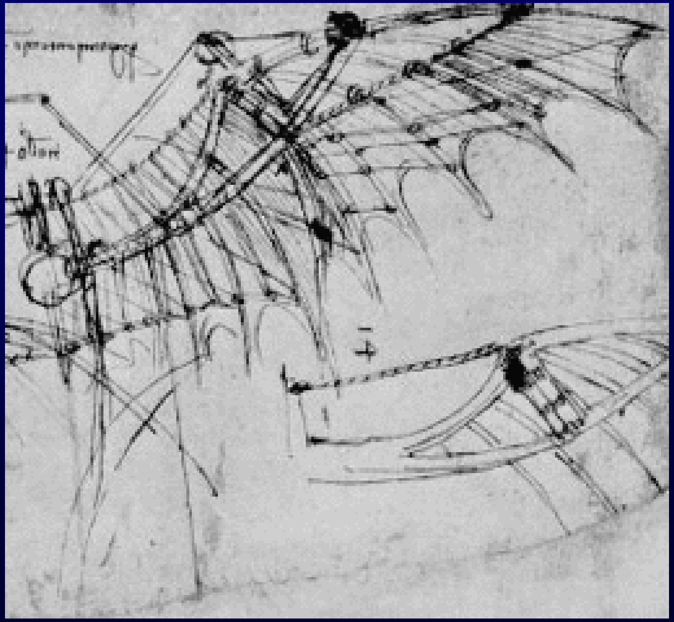
His doctoral research was an attempt to produce a ***physical device that explicitly mimicked the electrical action of a nerve***.

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)

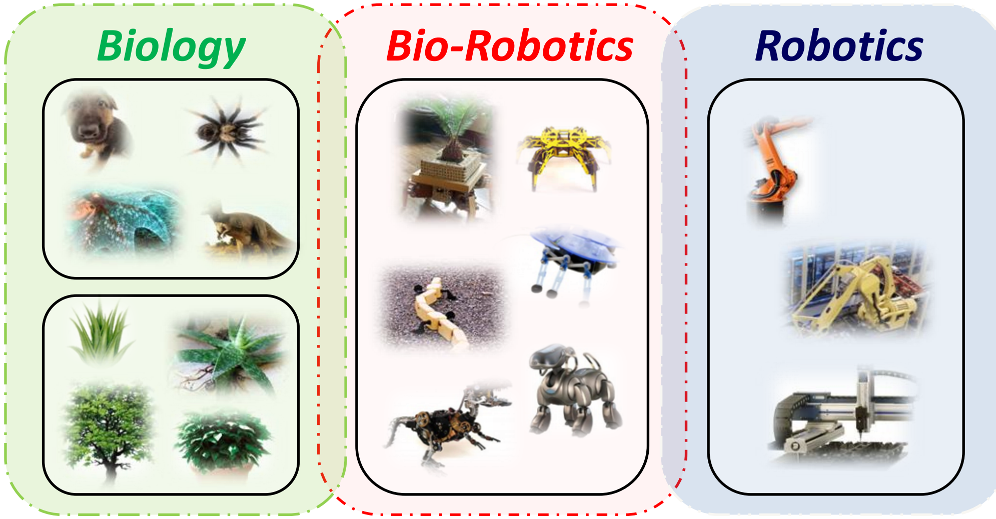
Otto H. Schmitt and his wife Viola

Chinese tried to make an artificial silk more than 3000 years

Leonardo da Vinci studied bird flight and designed some machines



Biorobotics Science and Engineering



… by providing tools/methods for scientists studying biological systems

Courtesy of M. Brega

<u>Biorobotics Science</u>: using robotics to ***discover new principles*** …

<u>Biorobotics Engineering</u>: 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

Biology as a Model

To identify the biological system(s) responsible for producing the desired characteristic

↓

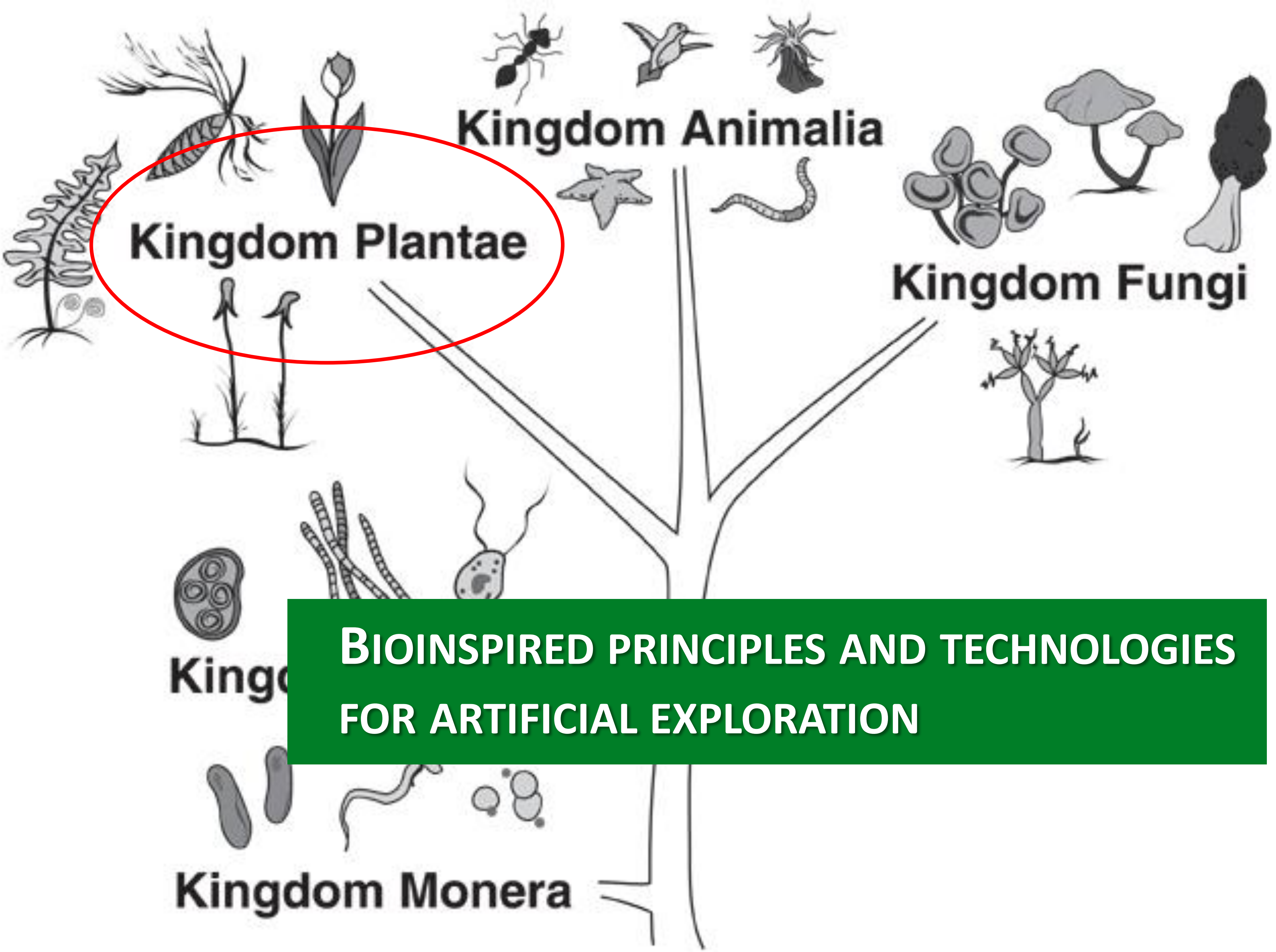
To extract the key principles underlying their biological function

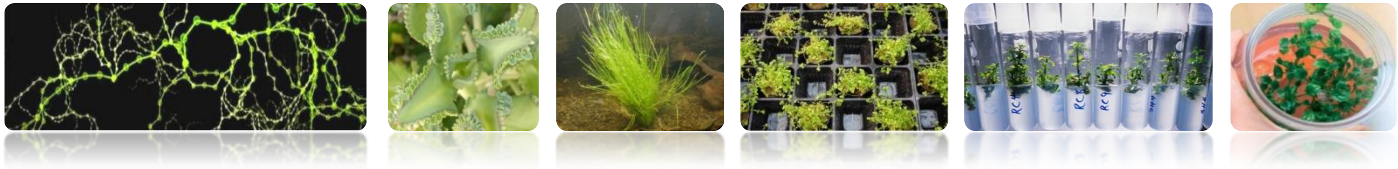
↓

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.

BIOINSPIRED PRINCIPLES AND TECHNOLOGIES FOR ARTIFICIAL EXPLORATION

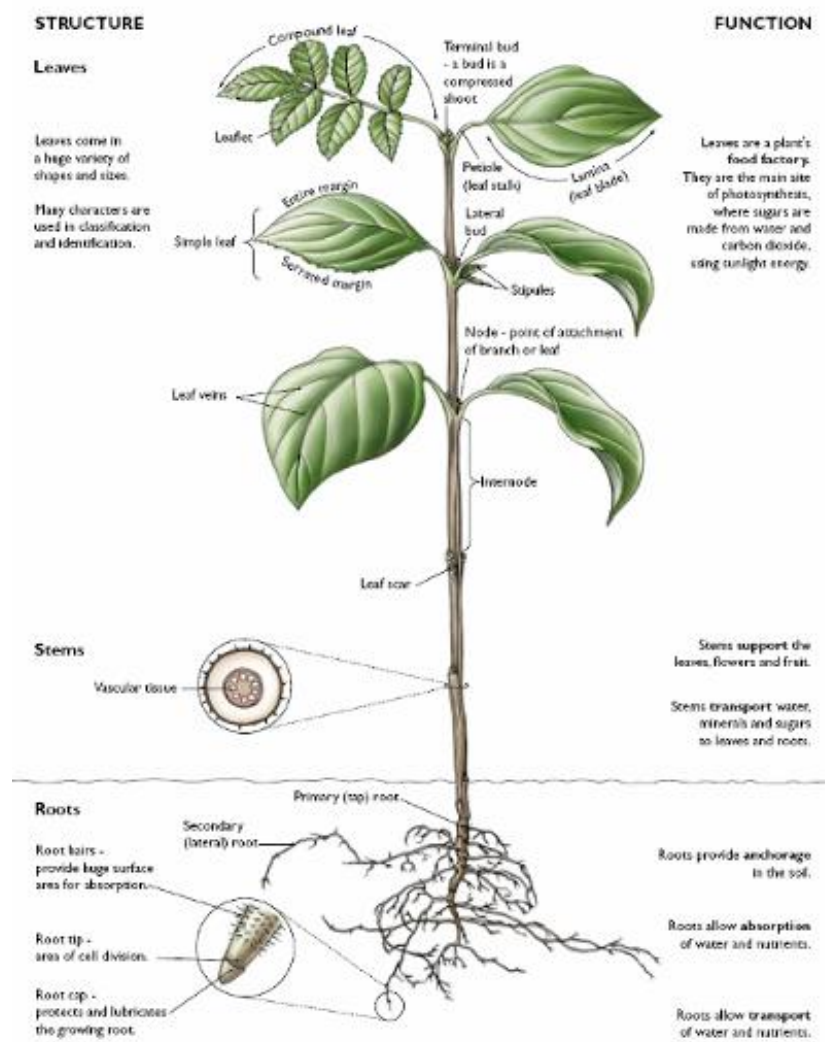




WHY A ROBOT MUST BE INSPIRED BY PLANTS?

PLANTS AS PASSIVE ORGANISMS

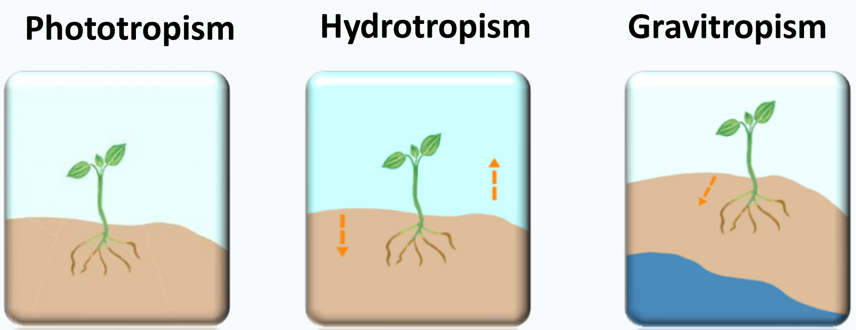
- No movement, in an animal meaning
- No communication with other plants or organisms
- No possibilities to escape from a hostile environment



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*

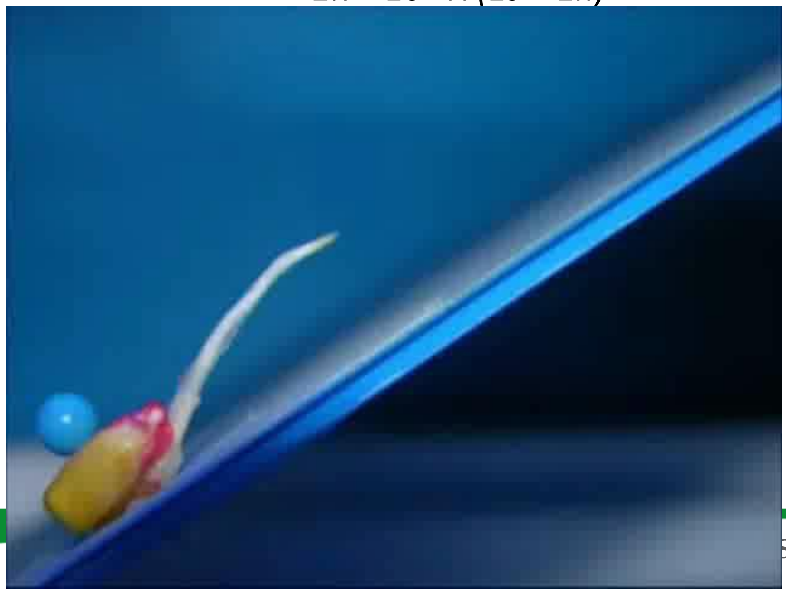


A young bean moves around to sense structures to be used as support.

A primary root follows the gravity

Videos courtesy of Stefano Mancuso (UNIFI)

2.7 · 10^{-4} X (1s = 1h)



Passive Actuation in Plants: The Pine Cone Movements

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.

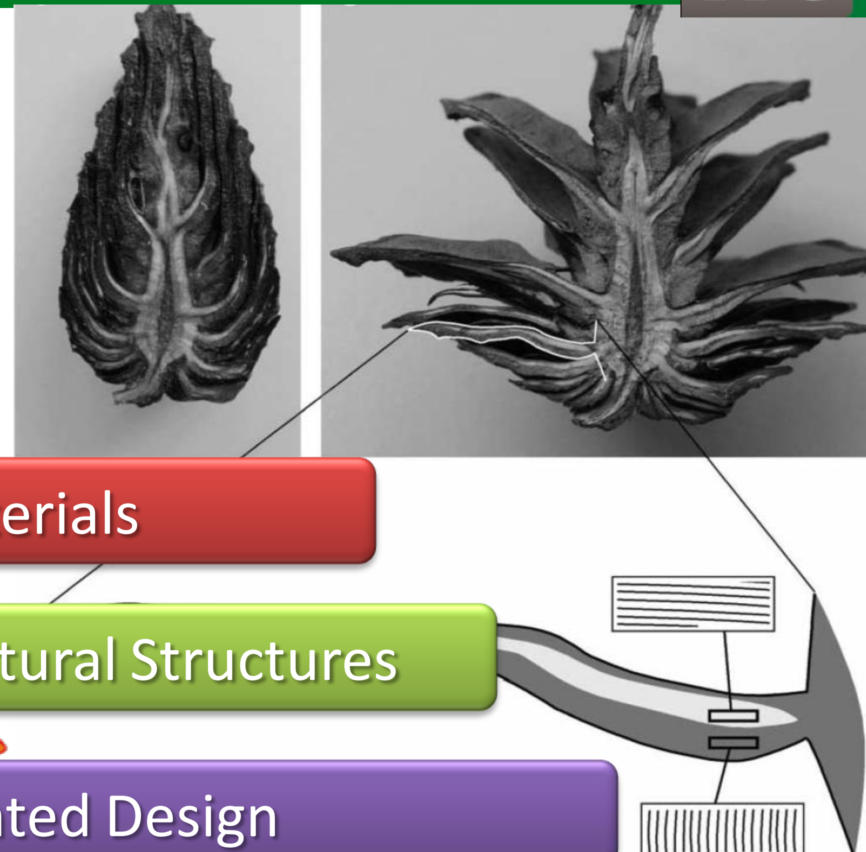
I. Burgert and P. Fratzl "Actuation systems in plants as prototypes for bioinspired devices", *Phil. Trans*. R. Soc. A 367, 1541-1557, 2009

C. Dawson, J. F. V. Vincent, A. M. Rocca "How pine cones open", *Nature* 390, 668 ,1997

Actuation Mechanism in Pine Cone

Swelling and shrinking of matrix polymers

Orientation of cellulose microfibrils in the scales of the pine co

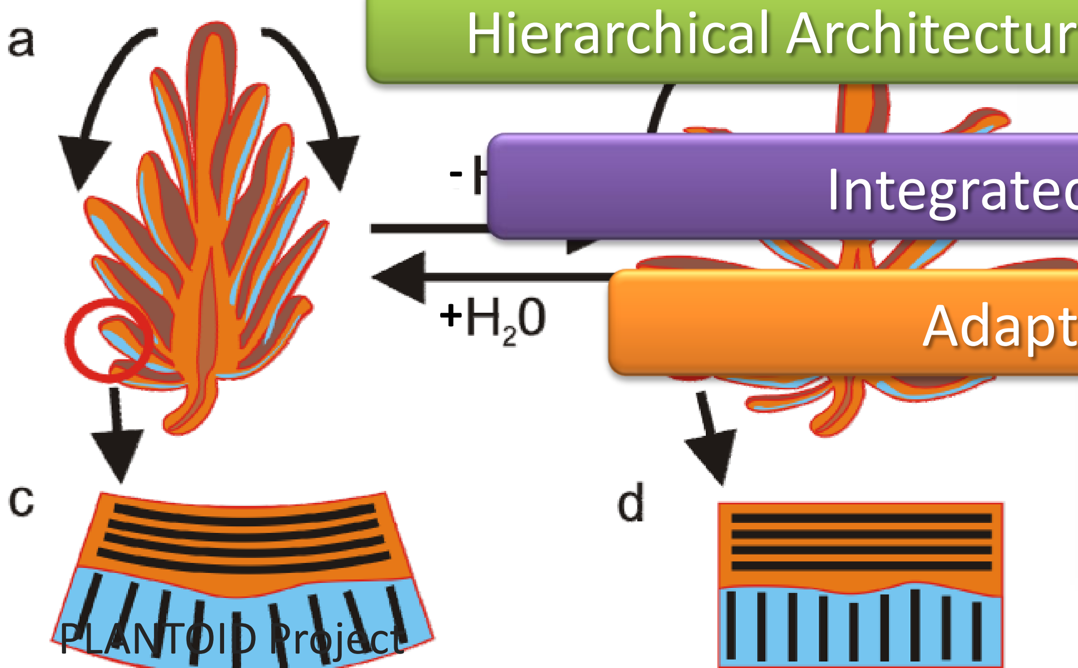


Multifunctional Materials

Hierarchical Architectural Structures

Integrated Design

Adaptive Behaviour

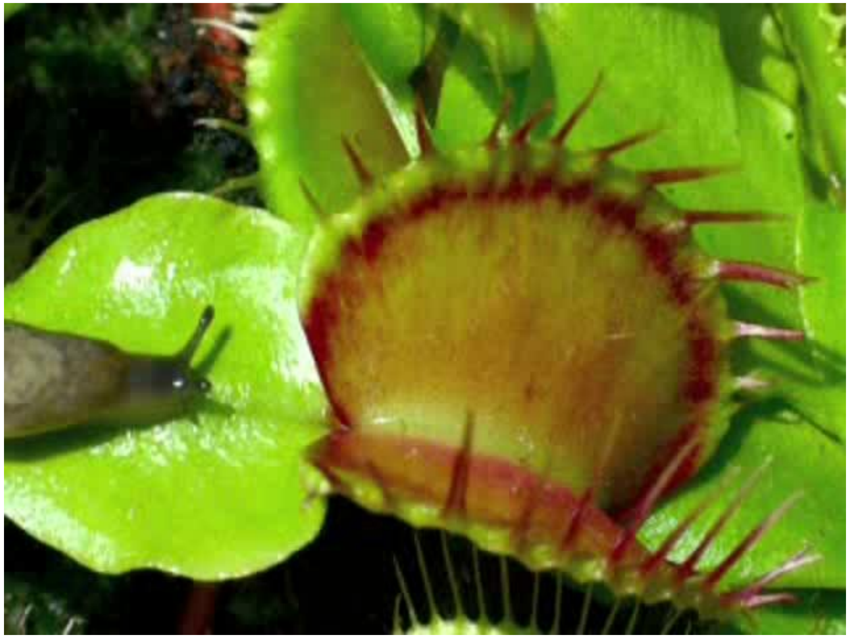


…stems in plants as prototypes for bioinspired devices", Phil. Trans. R. Soc. A 367, 1541-1557, 2009

C. Dawson, J. F. V. Vincent, A. M. Rocca "How pine cones open", Nature 390, 668,1997

PLANTOID Project

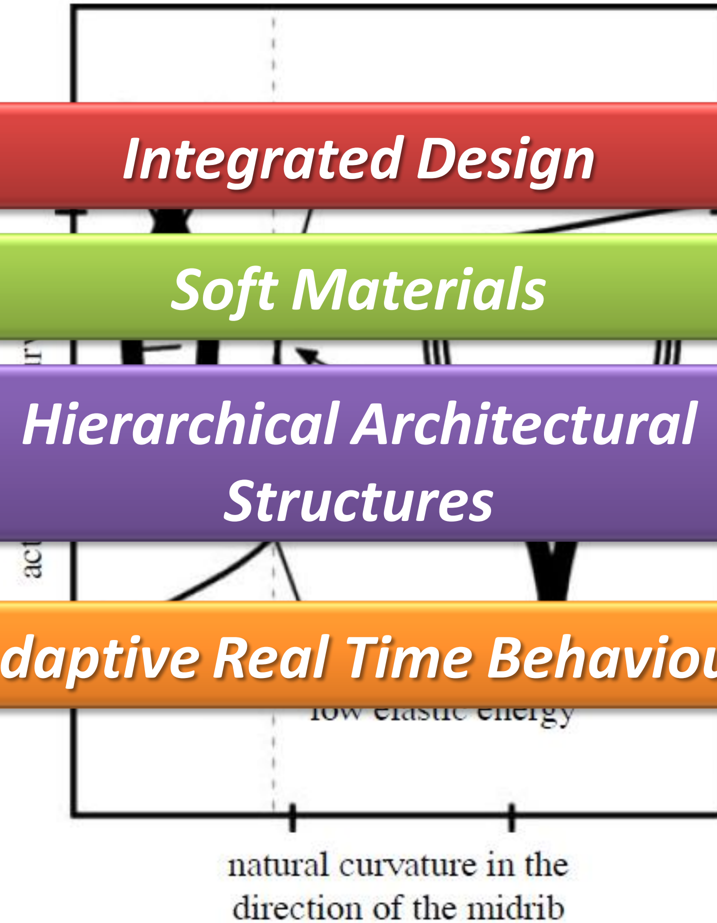
Active Actuation in Plants: Venus Flytrap



Video courtesy of Stefano Mancuso (UNIFI)

Venus flytrap (*Dionaea muscipula*)

(about 1s to close completely but only about 100 ms to "trap")



Integrated Design

Soft Materials

Hierarchical Architectural Structures

Adaptive Real Time Behaviour

This mechanism relies on geometrical <u>and materials</u> 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

C. Dawson, J. F. V. Vincent, A. M. Rocca "How pine cones open", Nature 390, 668 ,1997

R. Elbaum, L. Zaltzman, I. Burgert, P. Fratzl "The Role of Wheat Awns in the Seed Dispersal Unit", Science, 316, 2007

WHY PLANTS? (FOR A ROBOTICIST)

Rich

sensing and coordination capabilities

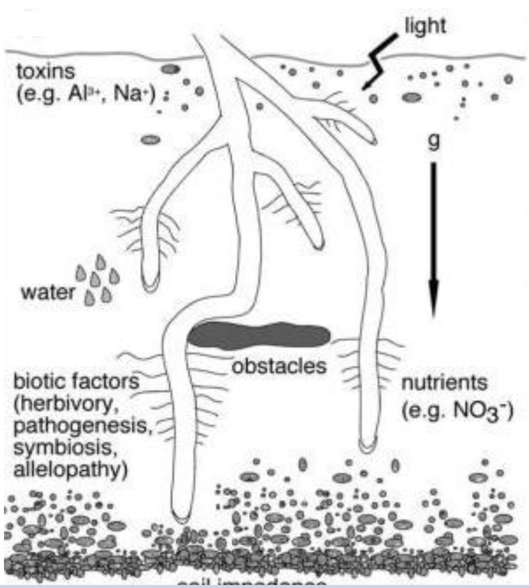
Adaptive growth and behaviour

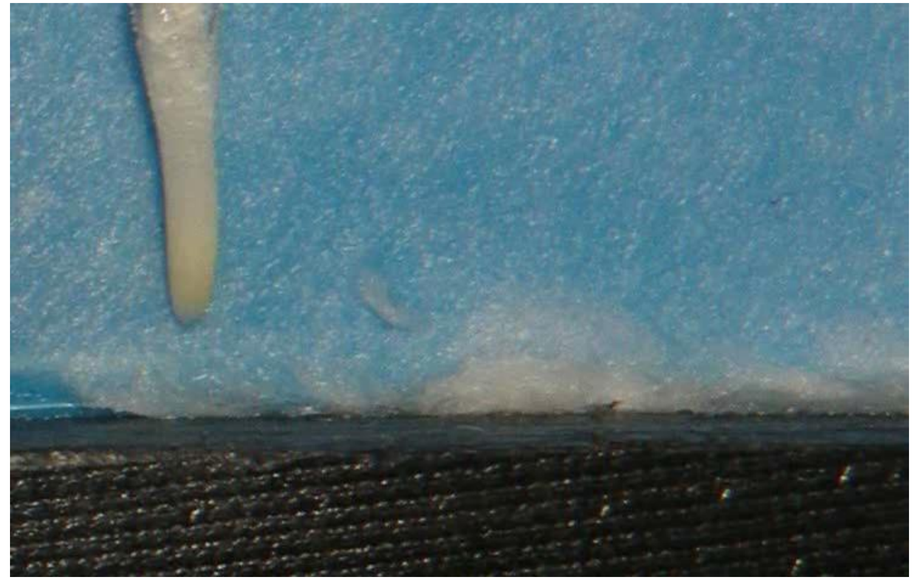
Energy-efficient actuation and high sustainability

Redundancy

WHY PLANT ROOTS? (FOR A ROBOTICIST)

Morphological computation, phenotypic plasticity and decision making



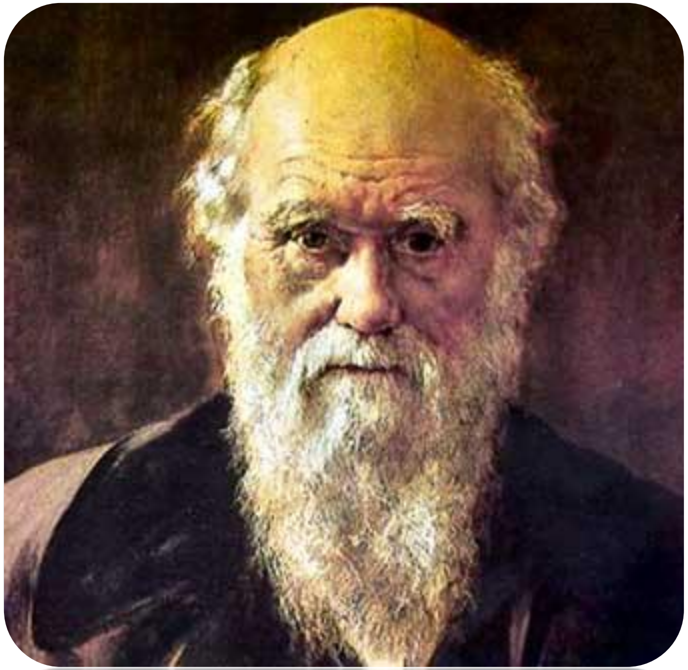


Physicochemical monitored parameters

Gravity	Water
Nitrogen (NH_4^+, NO_3^-)	Ions
Temperature	Salinity
Oxygen and other gases	Phosphorus
Light	Heavy metals
Electrical field	pH
Sound waves	

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 view point to the robotics perspective: **what are the plant's behavior and mechanisms that we want to imitate?**

Actuation system

Osmotic –based process

- Energy efficiency
- Low speed
- Strong actuation
- Low power consuption

Sensory system

Plants sensors

- Touch
- Humidity
- Gravity
- Ions, ...

Kinematics

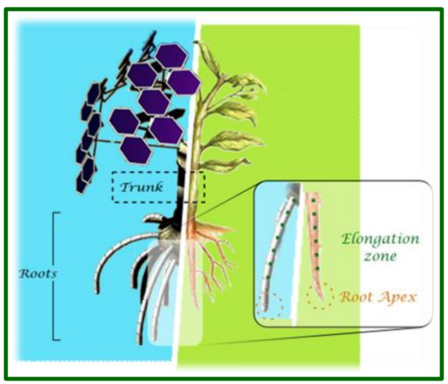
Elongation from tip

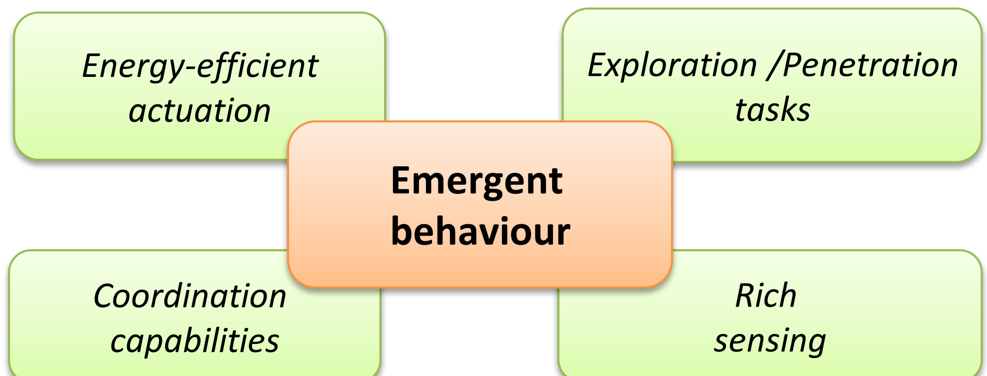
- Seedling & tip anchorage
- Control of friction
- Optimal soil deformation
- Penetration

Emergent behavior

Roots move in a responsive way

- Interspecific communication
- Nonrandom foraging
- Territoriality
- Kin selection, ...





B. Mazzolai, A. Mondini, P. Corradi, C. Laschi, V. Mattoli, E. Sinibaldi, P. Dario "A Miniaturized Mechatronic System Inspired by Plant Roots", IEEE Transactions on Mechatronics, Vol. 16, Issue 2, pp. 201 - 212, 2011. ***2012 TMECH Best Paper Award***

Mazzolai, B., Corradi, P., Mondini, A., Mattoli, V., Laschi, C., Mancuso, S., Mugnai, S., and Dario, P. "Inspiration from plant roots: a robotic root apex for soil exploration", in: Proceedings of Biological Approaches for Engineering, University of Southampton, 17-19th March, 2008, pp. 50-53.

Why Plant Roots

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Energy-efficient actuation

Exploration /Penetration tasks

Emergent behaviour

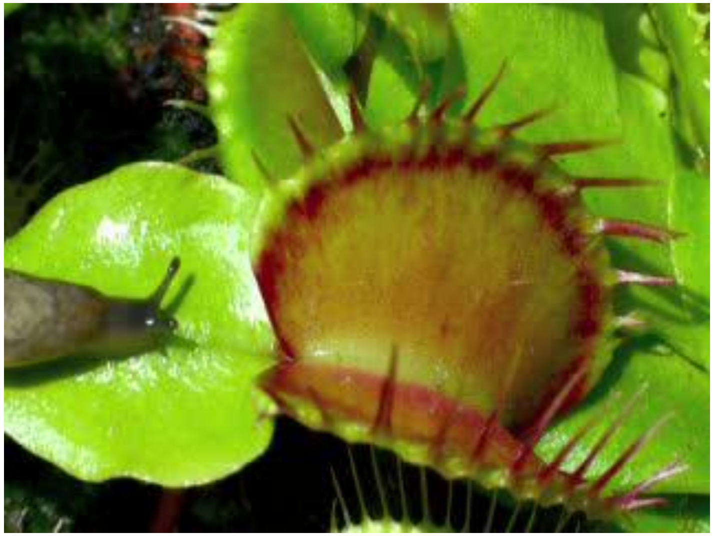
Coordination capabilities

Rich sensing

The osmotic principle as actuation strategy

Mimosa pudica

Videos courtesy of Stefano Mancuso (UNIFI)



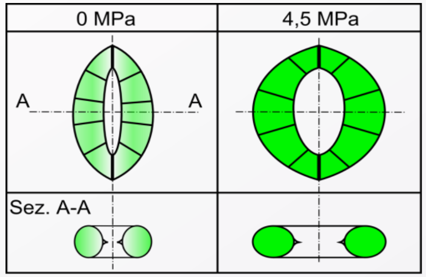
Genus *Stylidium*

Cnidocysts

ACTUATION SYSTEMS IN NATURE

Stomata's guard cells

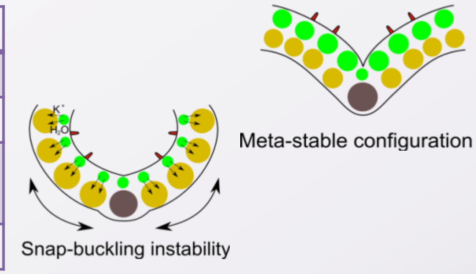
Max pressure	**4,5 MPa**
Velocity	**-**
Actuation time	**-**
Characteristic dimension	**~ 50 µm**
Reversibility	**Yes**



[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**

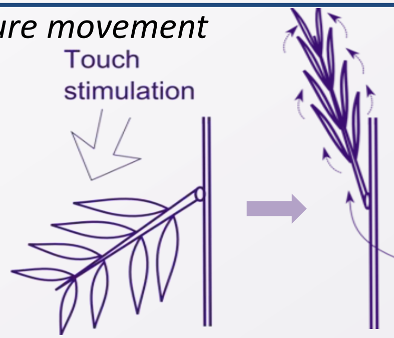


[Y. Forterre et al., Nature, 2005]

[M. Taya, Eapad, 2003]

Mimosa pudica: *leaves closure movement*

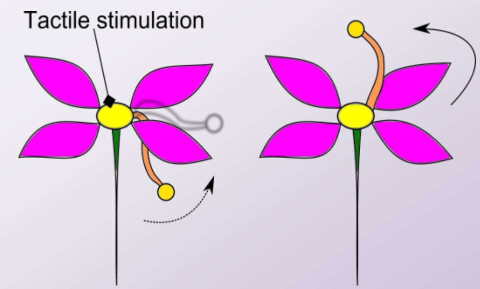
Max pressure	**-**
Velocity	**-**
Actuation time	**~ 2 s**
Characteristic dimension	**<1 mm**
Reversibility	**Yes**



[M. Taya, Eapad, 2003] [K. Oda and T. Abe, Journal of Plant Research, 1972]

Stylidium flower: *pollination movement*

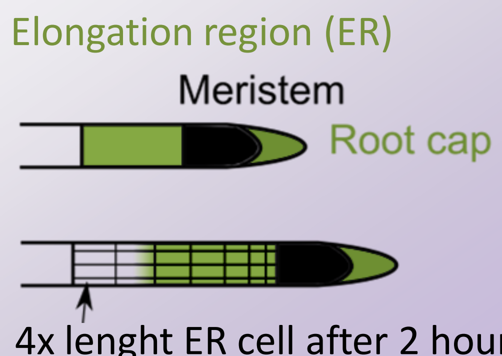
Max pressure	**-**
Velocity	**~150 rad/s**
Actuation time	**10 - 25 ms**
Characteristic dimension	**-**
Reversibility	**Yes**



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

Plant root apex

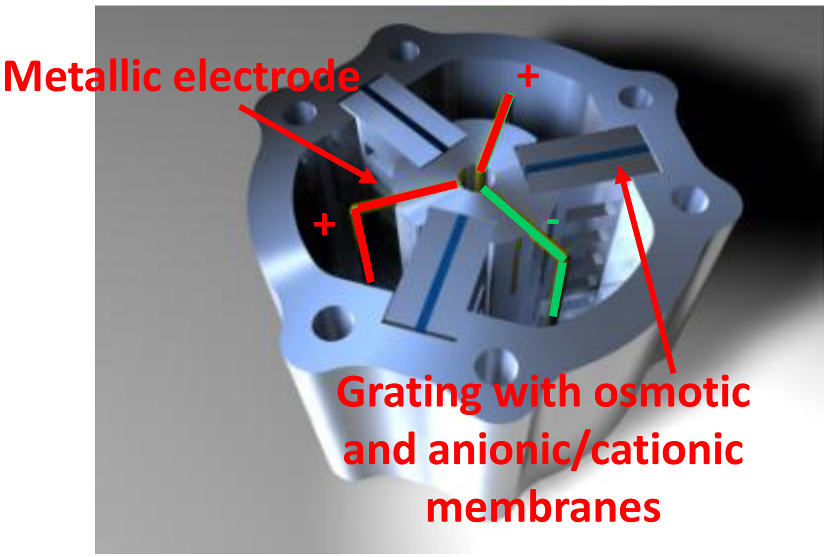
Max pressure	**~ 1 MPa**
Velocity	**~ 1 mm/h**
Actuation time	**-**
Characteristic dimension	**~1 mm**
Reversibility	**No**

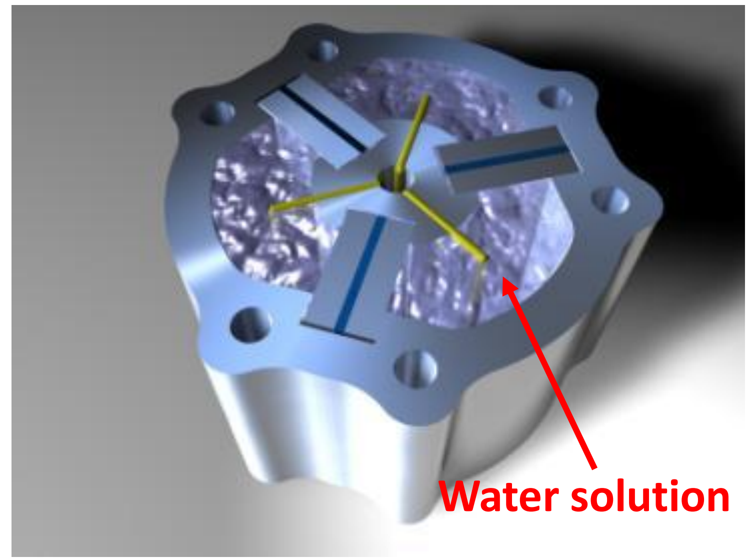


[L. J. Clark et al., Plant and Soil, 2003]

3-Cell Osmotic Actuator

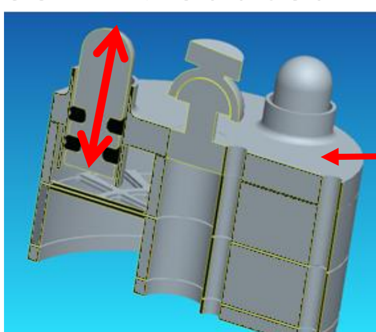
3-cell actuator: this solution maintains the osmotic process and allows the **steering** mechanism in a compact and easy way.

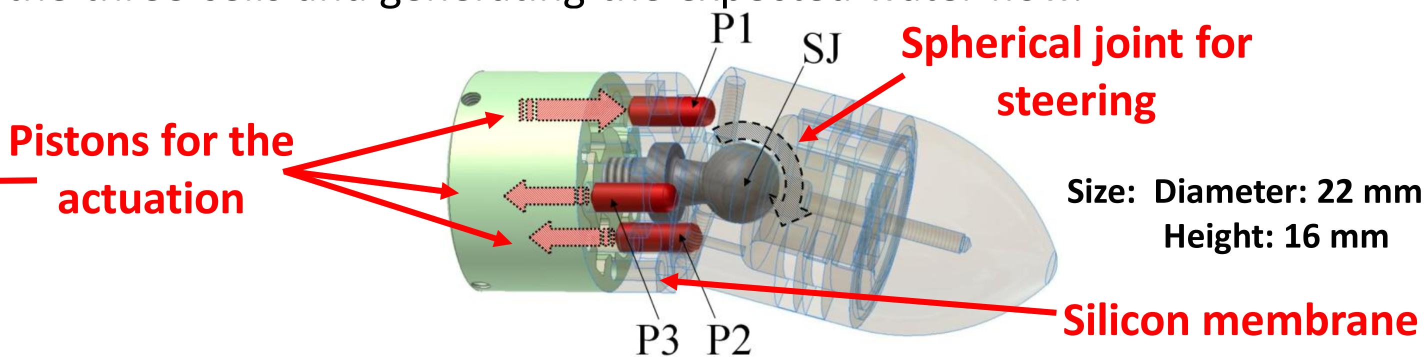




It is possible to set the potential of electrodes two at time or all together, changing the concentration across the three cells and generating the expected water flow.

In order to rotate the root apex in each direction a mechanism with **3 pistons have been introduced.**

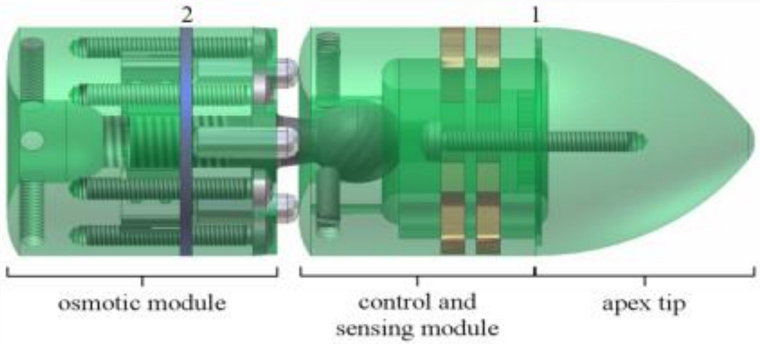




Size: Diameter: 22 mm
Height: 16 mm

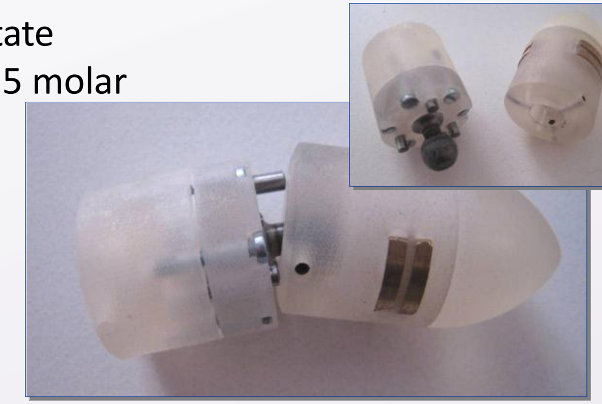
ACTUATION SYSTEM: FIRST PROTOTYPE

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 °



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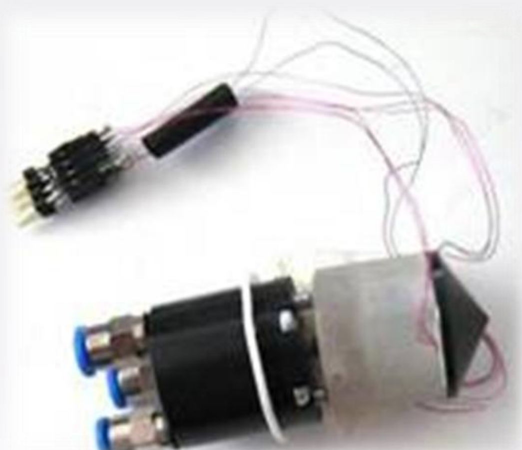
Hydraulic pressure system for testing the steering capabilities & gravitropic/hydrotropic response



First robotic apex

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- Territoriality
- Kin selection, ...

Energy-efficient actuation

Exploration /Penetration tasks

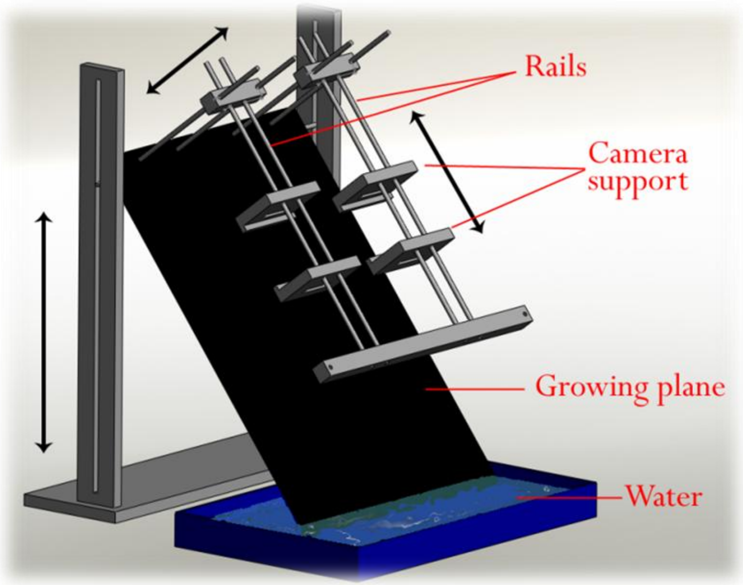
Emergent behaviour

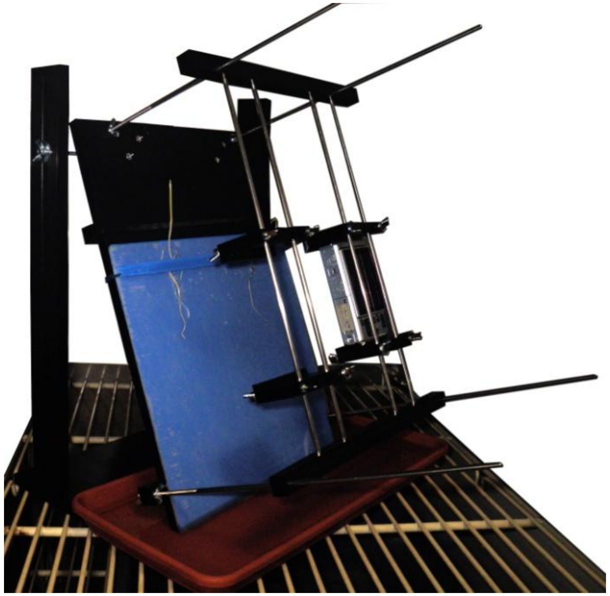
Coordination capabilities

Rich sensing

METHODOLOGY: SET-UP

Experimental observation of plant roots movements





Faced questions:

- Kinematics
- Tropism Mechanisms
- Collision detection
- Emergent behaviour

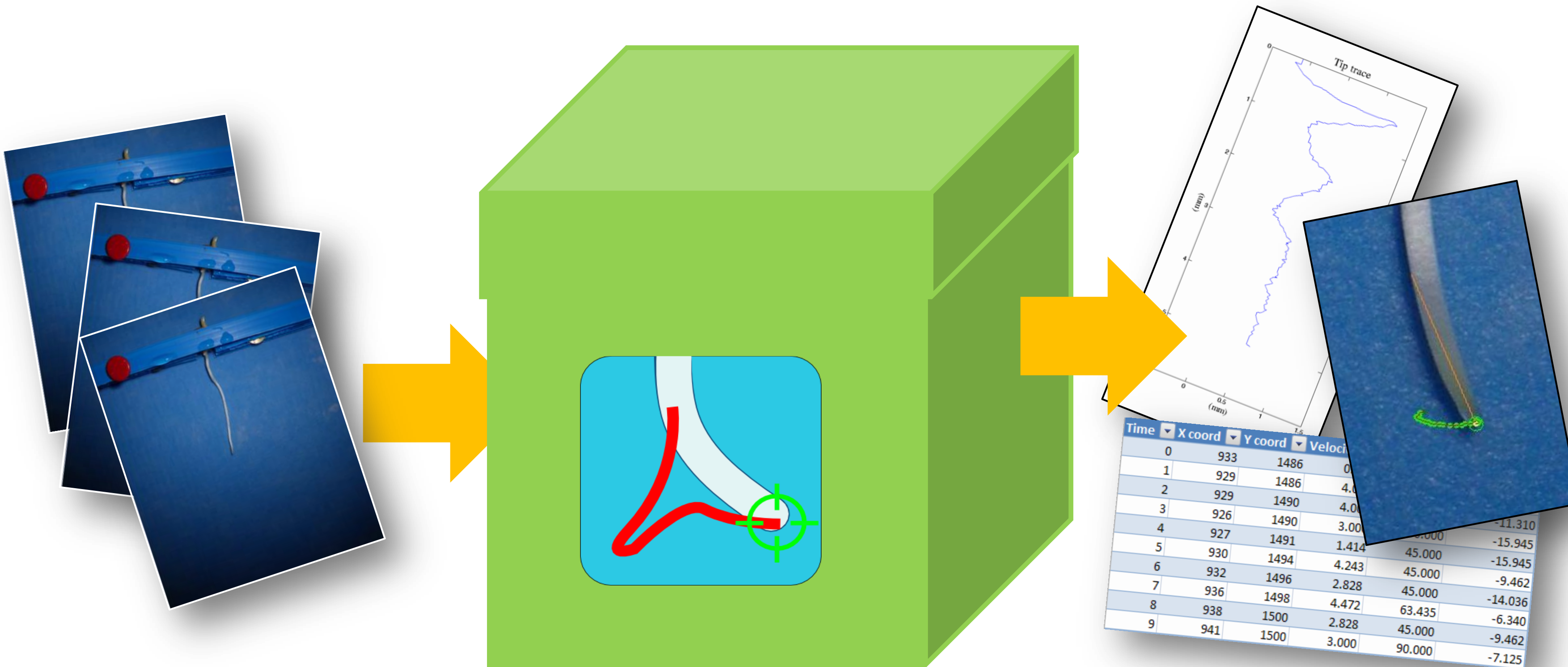
Simplifications:

- Terrain lack
- *2D* constrained growing

- HighResolution time-lapse capture
  - *12.1 megapixels*
- Controllated Chambres
  - *Temperature (24-25°C)*
  - *Umidity (saturated)*
  - *Dark cell*
- Seeds
  - *Mais Kubrick*
  - *Rice*

ARTT

Analyzer for **R**oot **T**ip **T**racks: a novel image-analysis tool

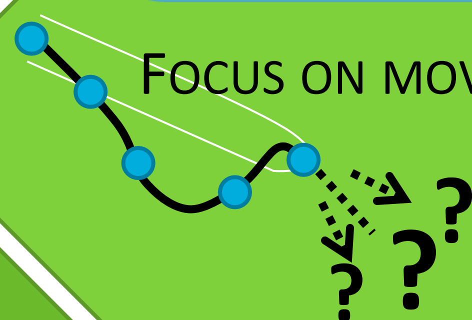


WHY A NEW SOFTWARE?

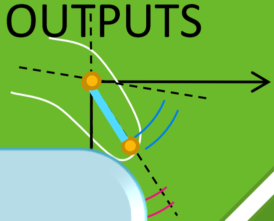
MASSIVE AUTOMATED ELABORATION

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

FOCUS ON MOVEMENTS

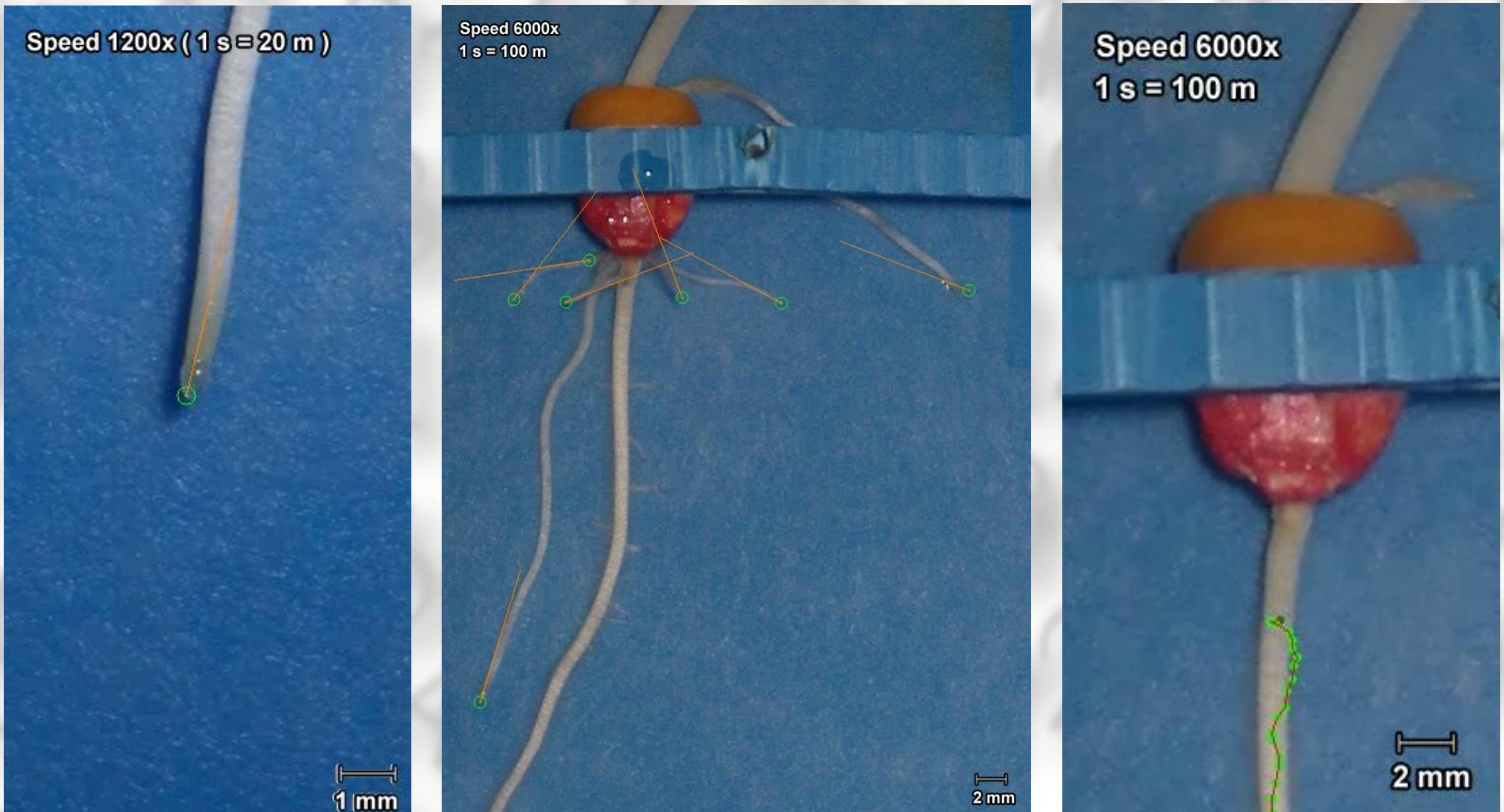


GENERAL SET OF OUTPUTS



- **Quantitative data:**
  - *Trajectory*
  - *Displacement*
  - *Velocity*
  - *Direction and Orientation*
  - *Generation of root tip traces*

LONG PERIOD OBSERVATION



Spatial resolution of 61 $\mu m\ px^{-1}$ with time lapse of 20 min
Images show tip movements at intervals of 80 min

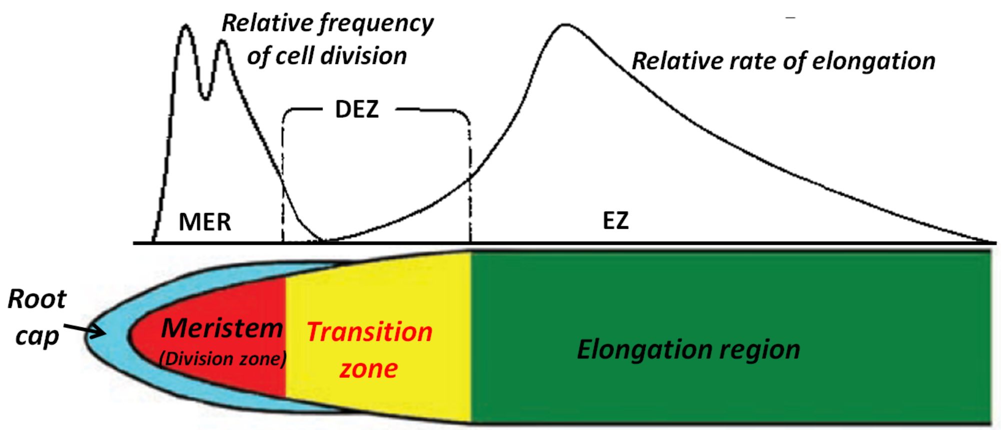
Popova L, Russino A, Ascrizzi A, Mazzolai B , Analysis of movement in primary maize roots, Biologia *67(3), 2012*.

Root Penetration Strategies

- Root Growth from the Tip
  - To avoid as much as possible frictional energy dissipation and tissue damages.
- Apex Anchorage
  - To avoid the root uplifting instead of penetration and to reduce buckling
- Circumnutational Movements
  - To find the paths with less mechanical impedance
  - To push the soil and small particles aside or to circumnavigate the particles with bigger diameter
- Frictionless Penetration
  - To avoid as much as possible frictional energy dissipation and tissue damages
- Morphological Changes
  - To optimize the interaction with soil

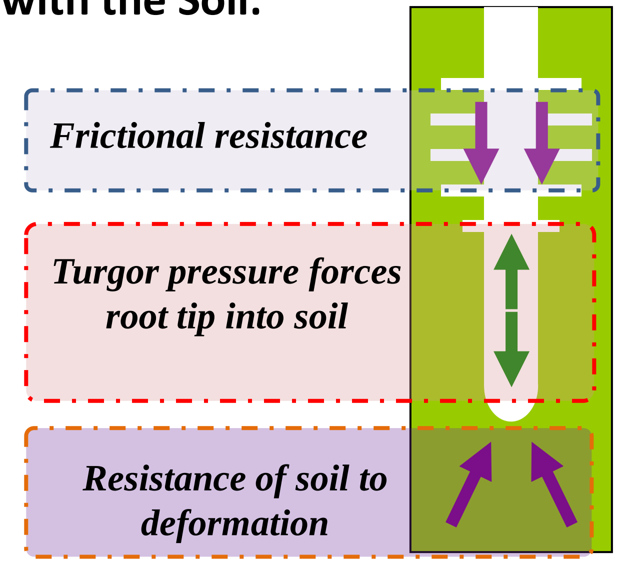
Root Growth from the Tip

Root Apex:

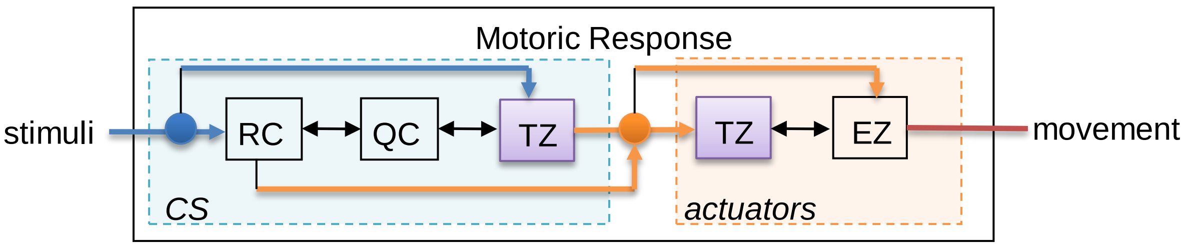


(modified from Baluška et al., Plant Signal Behav, 2009;
Ishikawa and Evans, Plant Physiol 1995)

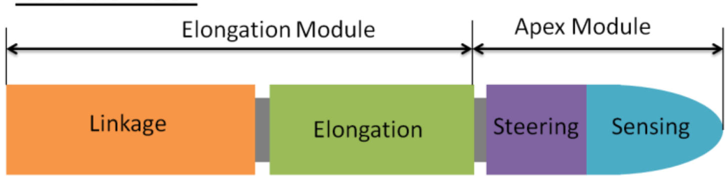
Root Apex Interaction with the Soil:



From Engineering Viewpoint:

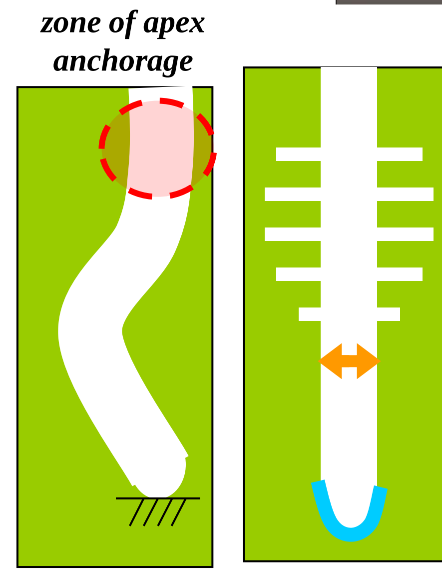


Robotic Root



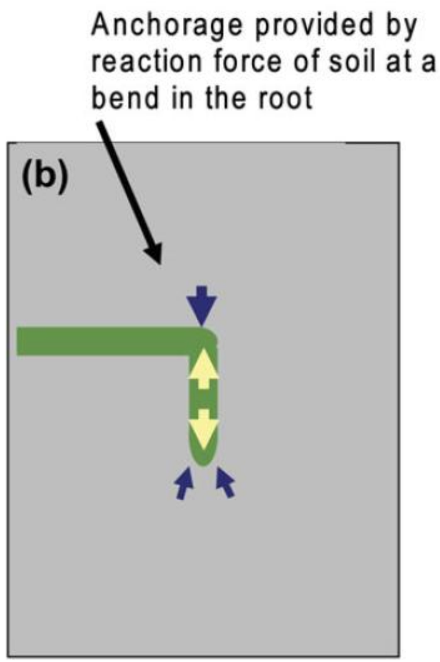
- RC = root cap
- QC = quiescent center
- TZ = transition zone
- EZ = elongation zone
- CS = control system

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

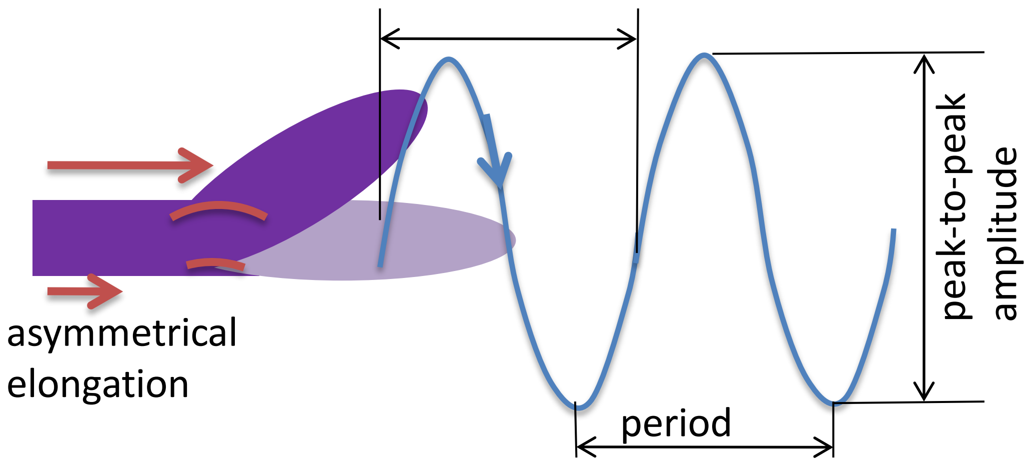


(Bengough et al., J Exp Bot, 2011)

• 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

Importance of the nutations in roots:



- facilitate **soil exploration** by finding pathways with less soil impedance
- may help **soil penetration** by displacing soil particles and by circumnavigating particles with bigger diameter (Hirota, J Jap Soc Grassl, 1976; Hirota, Plant Cell Physiol, 1980; Vollsnes et al., Eur J Soil Sci, 2010)
- **anchorage** in flooded soil (Inoue et al., Ecol Res, 1999)

Circumnutation Movements

Nutational movements:

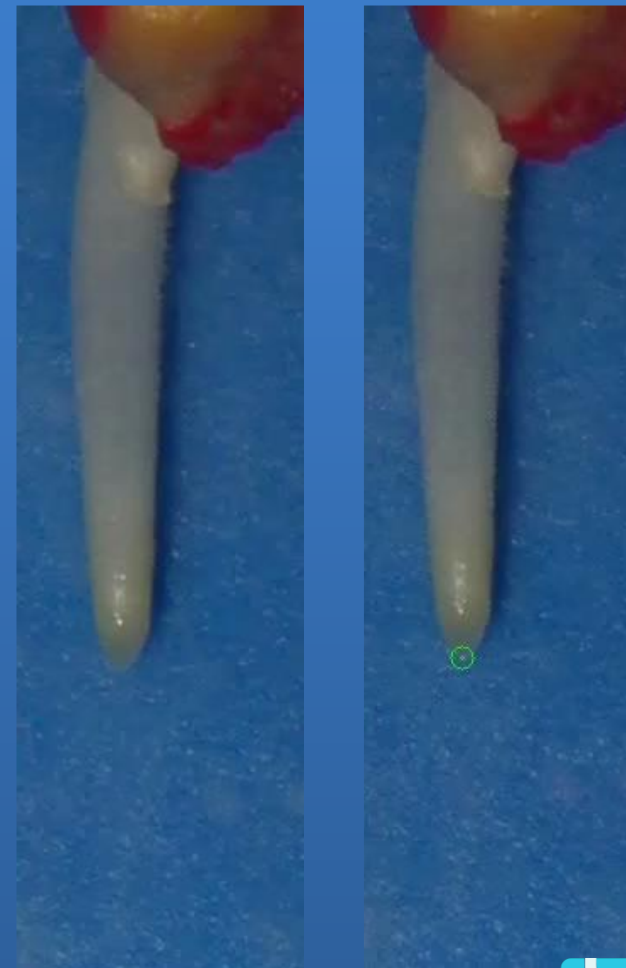
• pendulum *

1 s = 10 min

• pendulum
½ period 26-66 min

• waving and spiraling
period 46-110 min

• waving and spiraling *



1 s = 20 min

* Migliaccio et al., Plant Signal Behav, 2009

Circumnutation Movements

- up-down waving

1 s = 30 min

•up-down waving
period 38-110 min
• wave periods and amplitudes are not correlated

- micronutations *

1 s = 20 min

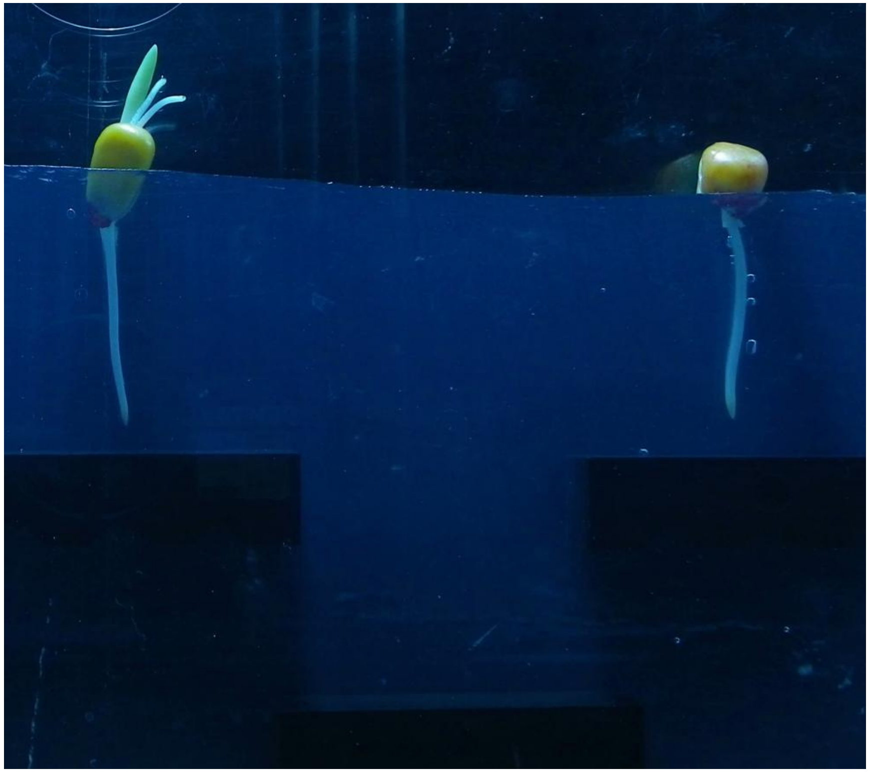
Shabala and Newman, Physiol Planatarum, 1997;
Walter et al., Plant Cell Environ, 2003

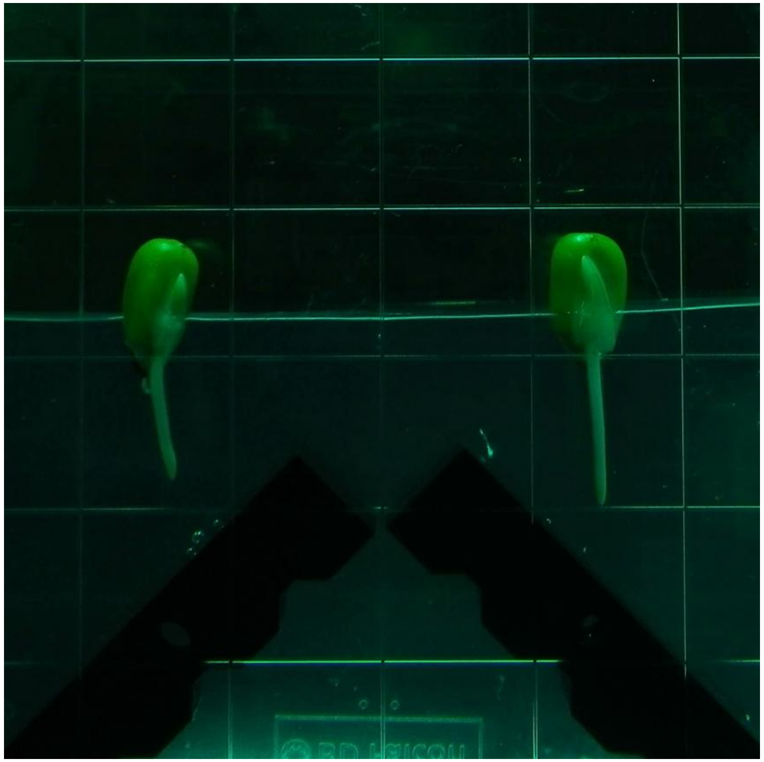
Obstacle avoidance behaviour

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

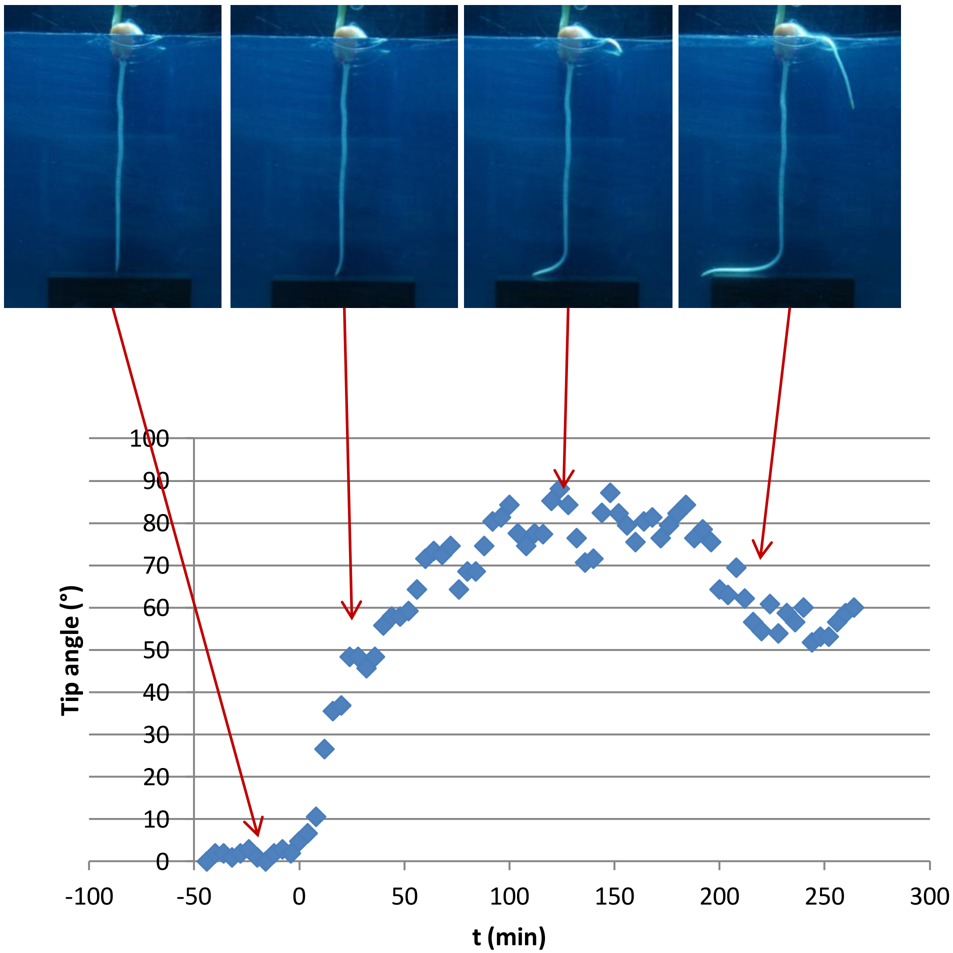
1) approaching to barrier
2) transient period after first contact
3) stable period during obstacle avoidance in primary and lateral roots.

Root tip to obstacle angle approximately 45° (Massa and Gilroy, Plant J. 2003; Massa and Gilroy, Adv. Space Res., 2003)



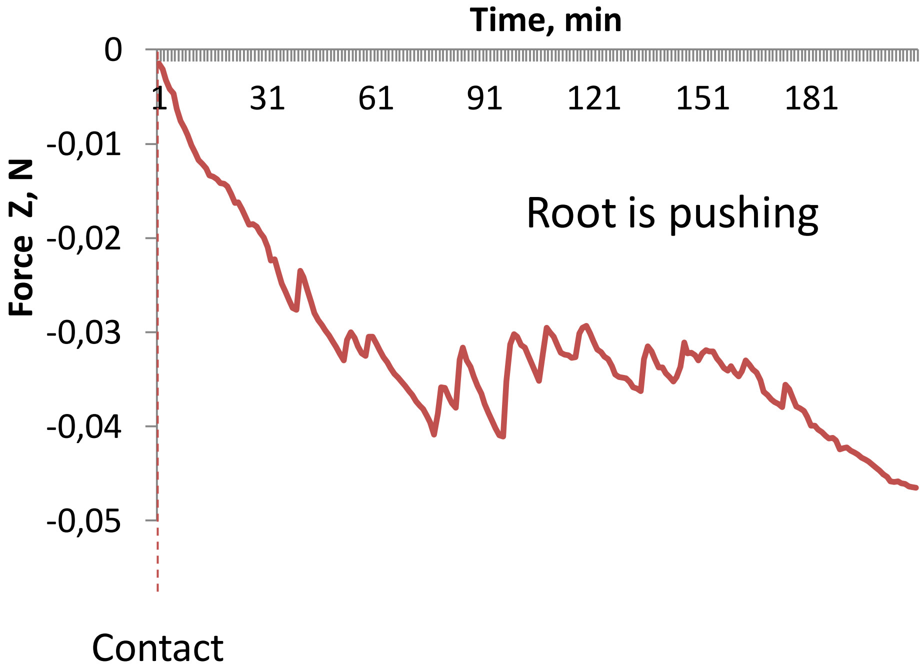


Flat obstacles



Preliminary results

What does it happen when the substrate cannot be penetrated?



The low friction properties of penetrating roots:

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

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

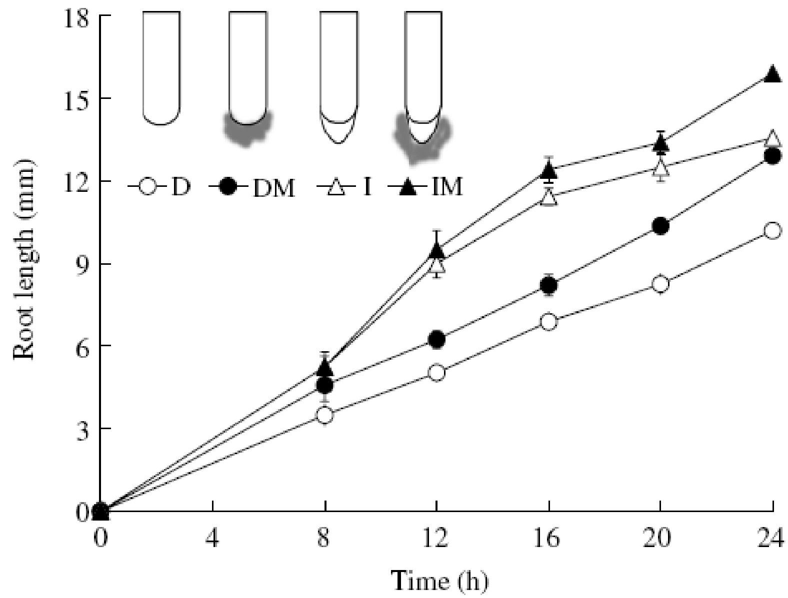


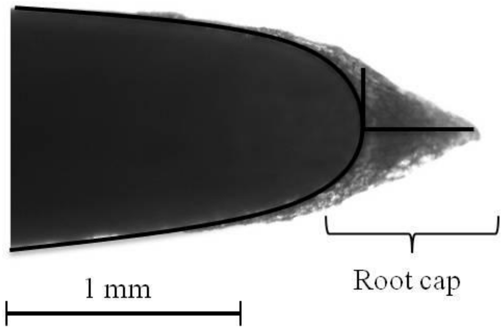
FIG. 1. Root length increment in compact soil during 24 h growth. Values are from seven to nine replicates. D, Decapped; I, intact; M, 2 μL mucilage added.

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

	Mucilage treatment (MT)	Decapping treatment (DT): Decapping	Decapping treatment (DT): Intact
	Mucilage	0·288 ± 0·005	0·222 ± 0·007
	Non-mucilage	0·328 ± 0·029	0·272 ± 0·006
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 $P \geqslant 0·05$.

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



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

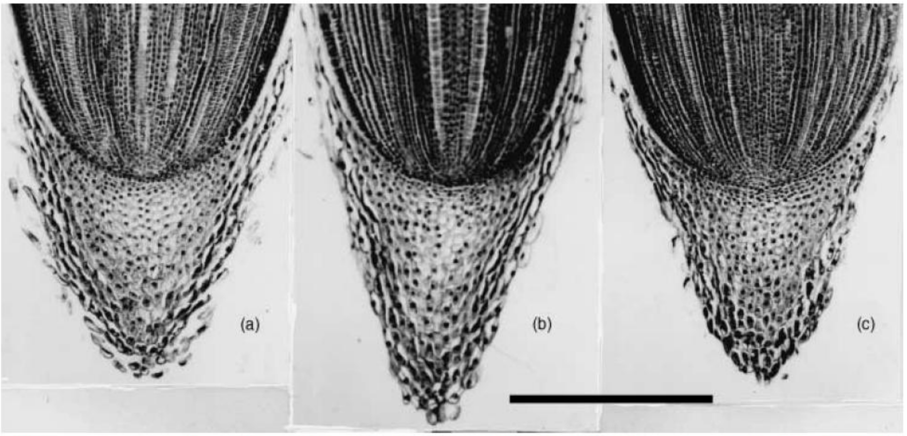
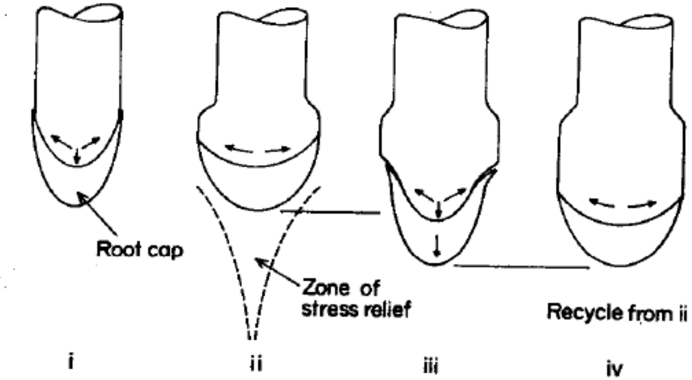


Fig. 1 Median longitudinal sections (×100 magnification) of root caps typical of this study of the effect of sand compaction. (a) Root tip after 64 h of growth on moistened filter paper (day 0 sample). (b Root tips grown for 24 h in loose sand. (c) Root tips grown for 24 h in compact sand. Bar, 500 μm.

(From Iijima et al., New Phytol, 2003)

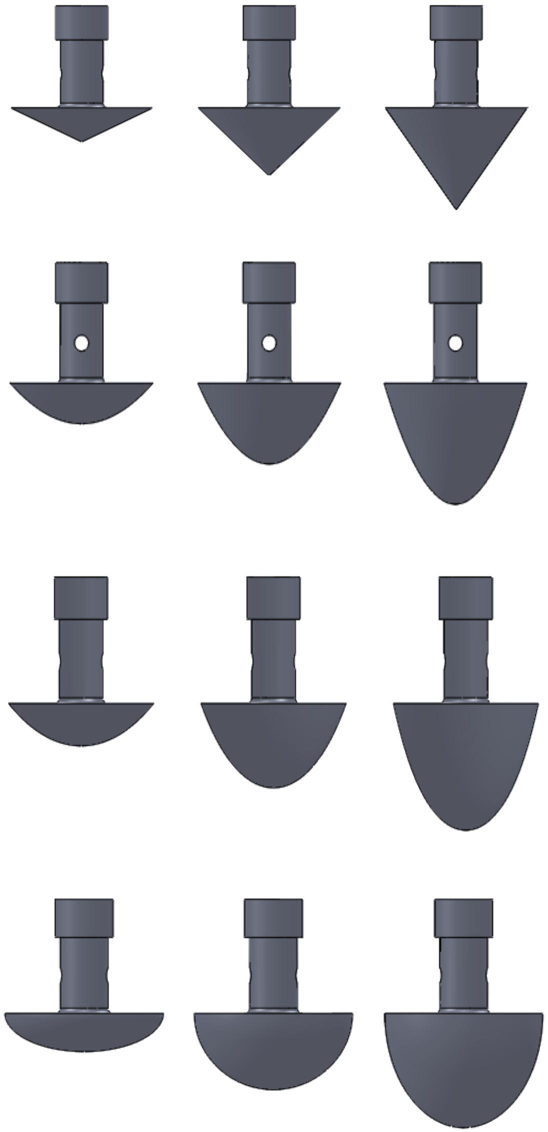
- Mechanical impedance effects
  - the elongation rate decreases
  - the root diameter increases



(From Abdalla et al., J agric Engng Res, 1969)

- Root shrinking & swelling

STUDY OF THE TIP SHAPE

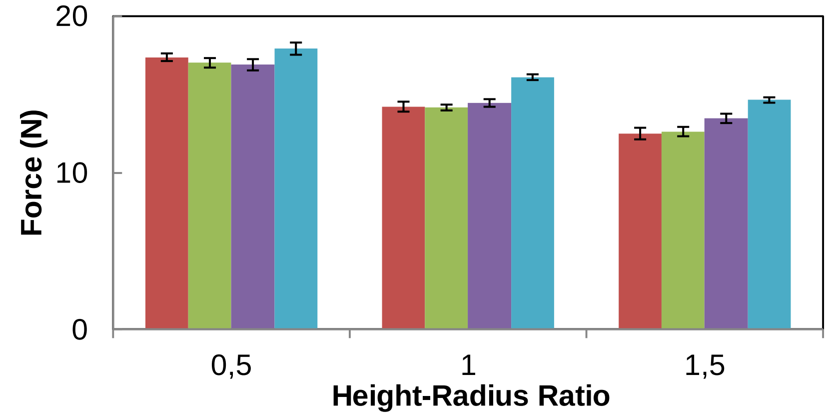


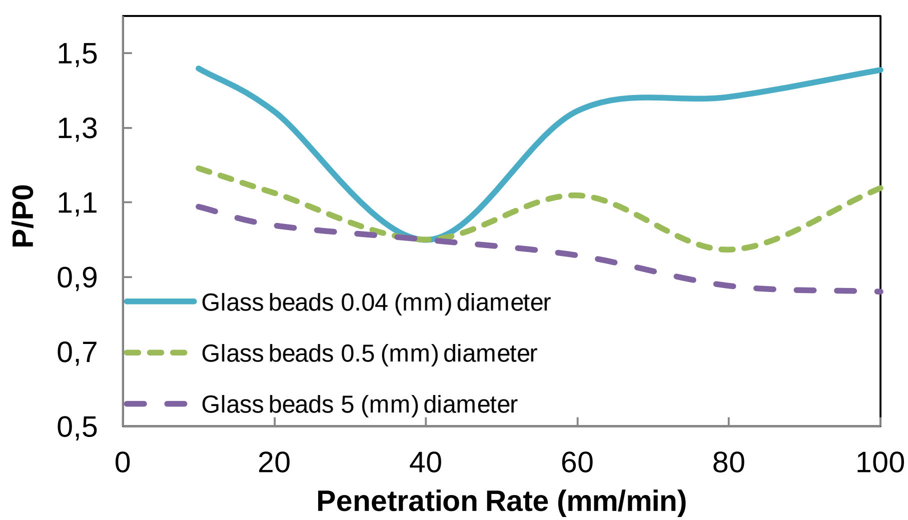
- **4 different tip profiles**: conical, parabolic, catenary, and elliptical
- **3 tip diameters**: 10 mm, 20 mm, and 30 mm (height –radius ratio 1.5)
- **3 height-radius ratios**: 0.5, 1, and 1.5
- **3 diameters of glass beads**: 0.04 mm, 0.5 mm, and 5 mm

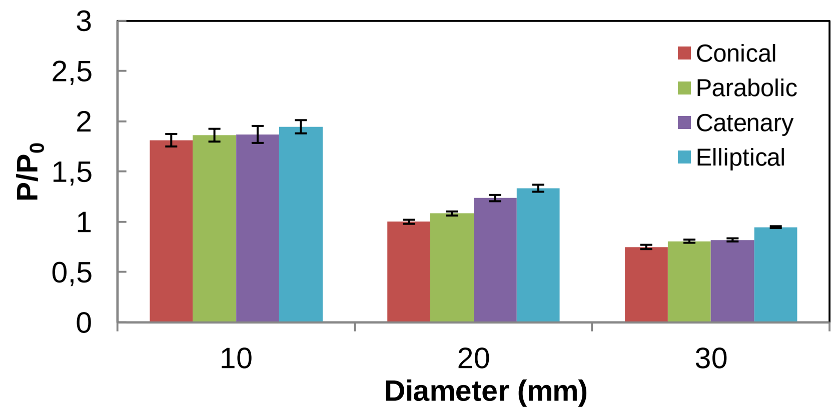
Study of the tip shape

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







WHY PLANT ROOTS

From the biological view point to the robotics perspective: **what are the plant's behaviour and mechanisms that we want to imitate?**

Actuation system

Osmotic process-based

- Energy efficiency
- Low speed
- Strong actuation
- Low power consuption

Sensory system

Plants sensors

- Touch
- Humidity
- Gravity
- Ions, …

Kinematics

Elongation from tip

- Seedling & tip anchorage
- Control of friction
- Optimal soil deformation
- Penetration

Emergent behaviour

Roots move in a responsive way

- **Interspecific communication**
- **Nonrandom foraging**
- **Territoriality**
- **Kin selection, …**

Energy-efficient actuation

Exploration /Penetration tasks

Emergent behaviour

Coordination capabilities

Rich sensing

EMERGENT ROOTS BEHAVIOUR

Plant roots deal with multiple mechanical and sensorial stimulations showing phenotipic plasticity

Minimization of energy consumption

Physical embedding and task distribution

Apices coordination for the optimization of nutrients uptake

Lack of a single centre of control which is distributed

Plants recognize and discriminate against the roots of adjacent conspecifics and thus possess self-recognition

A. Trewavas, Plant intelligence, Review, Naturwissenschaften, 2005.

A. Trewavas, A. (2002), Mindless mastery, Nature, Vol 415

A. Hodge, Root decisions, Plant, Cell & Environment, 32, 628-640, 2009.

M. Ciszak, D. Comparini, B. Mazzolai, F. Baluska, T.F. Arecchi, T. Vicsek, S. Mancuso, Swarming behavior in plant roots, PLoS One, Vol 7, 1, 2012.

EMERGENT ROOTS BEHAVIOUR

Developed model to describe Emergent Roots Behaviour:

Growing *Conditions*:

- Availability of all the required resources
- Uniform distribution of nutrients

Growing *Target*:

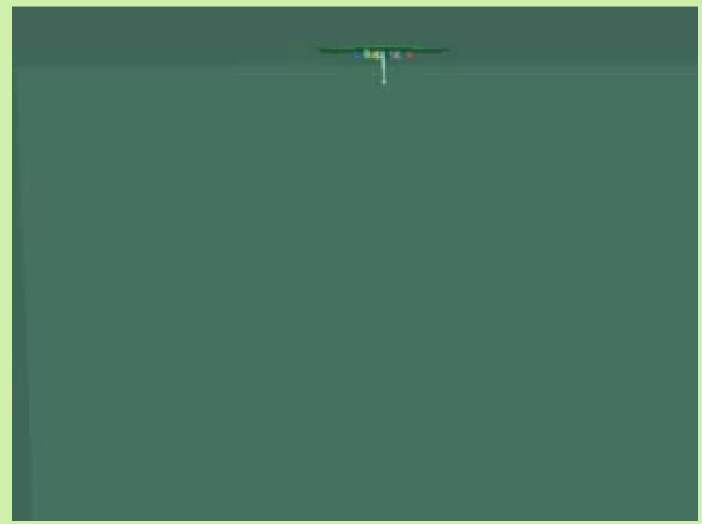
- Gravity
- Proximity

Biological model

VEL X $3{,}6 \cdot 10^4$ (1S=10H) PERIOD = 170H

Artificial model

12 ROOTS $W_G = 0.1$ $W_P = 0.5$



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

*A. Russino, A. Ascrizzi, D. Di Baccio, C. Laschi, S. Mancuso, B. Mazzolai, "Root decisions: a model of self-organizing and collective adaptive behaviour", **Plant, Cell & Environment** (submitted).*

*M. Ciszak, D. Comparini, B. Mazzolai, F. Baluska, T.F. Arecchi, T. Vicsek, S. Mancuso, "Swarming behavior in plant roots", **PLoS One**, in press.*

*A. Russino, D. Di Baccio, A. Ascrizzi, C. Laschi, B. Mazzolai, Decision of growing direction in plant roots: a Swarm based approach for biorobotic applications, 1st International Conference on Applied Bionics and Biomechanics, **ICABB-2010**", Venice, October 14-16, 2010.*

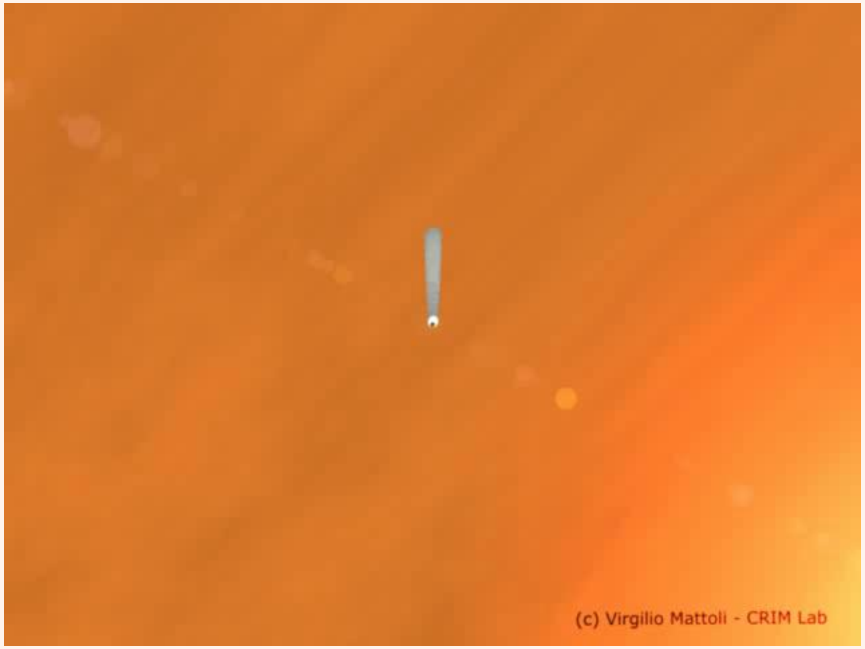
Application Scenarios

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)



Future and Emerging Technologies

THE PLANTOID PROJECT

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

Plantoid N 293431

INNOVATIVE ROBOTIC ARTEFACTS INSPIRED BY PLANT ROOTS FOR SOIL MONITORING

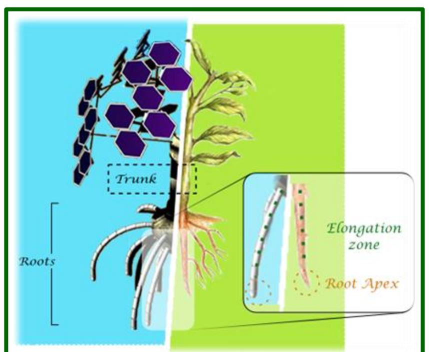
PROJECT DURATION:
36 months

STARTING DATE:
May 1, 2012

COORDINATOR:

Barbara Mazzolai

IIT@SSSA



EVALUATION SCORE 15/15

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CONCLUSIONS

• 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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Future and Emerging Technologies

PLANTOID
(contract no. 293431)

+ EPPN Workshop Organizers !

Center for MicroBioRobotics

Thank you!

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BARBARA.MAZZOLAI@IIT.IT

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