BIOMIMETIC TRANSFER OF PLANT ROOTS FOR PLANETARY ANCHORING

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Abstract

The task of autonomously anchoring spacecraft on the surface of any celestial body is extremely challenging. Weight restrictions do not allow for massive design; lacking external control calls for compliant drilling behavior. In search for a new concept we investigated biological mechanisms of ground anchoring.

Plants are the first organisms to settle in any type of empty habitat. The roots play an important role during settling providing scalable anchoring. This feature is a consequence of longitudinal growth processes at the tip of the roots (apices) and radial growth on the overall root allowing them to increase in size and strength as well as adapting to changes in external loads. The growth direction of the apex is controlled by a simple set of mechanical and chemical sensors in the transition zone. Root apices also exchange information between each other for coordination.

We transfered the technical features of roots concerning anchoring strategy, actuation, and control aspects into engineered concepts. Extending the 'root' at the tip reduces friction with the substrate, a new type of osmotic actuation works without few moving parts and consumes low energy. A distributed control architecture allows for individual and intra-individual steering, negotiating obstacles and ensuring tight anchoring. Finally we present a technical root integrating the current technological possible solutions.

INTRODUCTION

On first sight it appears strange to focus on living nature in search of new design concepts for spacecraft. However, plants represent a major fraction of living beings on Earth and have conquered almost any surface on our planet. Although they cannot actively move, plants are the first settlers in a hostile environment, making path for a habitat that can then be settled by all kinds of animals. After having been placed into a new environment - usually as a seed and being transported passively - they need to anchor in the substrate and exploit the available resources in order to grow. From this description it becomes clear, that roots play an important role for a successful establishment on a new site. The roots need to provide mechanical anchoring, preferably adaptive to changing size of the stem above ground. Each single root has to move through the substrate, orienting along the gravity vector, negotiating obstacles, and lo-

cating resources at the same time while balancing the external loads applied. The entire behavior is achieved by an osmotic actuation system that is steered by a distributed set of simple controllers located in the tip of each root - the apex. During a planetary mission, a spacecraft can be seen as going through similar stages as a plant in the beginning of its life. After having landed, the once mobile spacecraft might anchor and probe the substrate for scientific reasons. Inspired by this analogy, a team of biologists and engineers investigated both the actuation and the control mechanisms of plant roots in the focus of a biomimetic transfer for conceptually novel anchoring solutions for exploratory spacecraft [1].

Plants and their roots

Plants usually have an aerial part and a root system. Plant roots of, e.g., the mesquite (genus *Prosopis*) may extend down more than 50 m to

reach groundwater. Annual crop plants develop a root system that can usually grow until 2.0 m in depth and extend laterally to distances up to 1.0 m. As a general rule, the annual production of roots may easily surpass that of shoots, so the above-ground portions of a plant can be seen as the tip of an iceberg. As plants are mostly sessile, they have developed certain growth responses - so called tropisms - which allow them to respond to changes in their environment. The best known stimuli for tropisms are light, gravity, touch, and humidity [2, 3]. Together, these rather simple mechanisms allow plants to conquer almost each type of environment. In doing so, root systems often far exceed in mass and length the above-ground portions of the plant, being provided with few to many main roots and thousands of ramifications. In spite of their delicate structure, the spiraling forward thrust of the root tips and the pressure of their expanding cells are sufficient to split solid rock. Plant tissue expands in tight places by taking up water via osmotic mechanisms, leading to an overall increase in size both by cell expansion and division. In order to provide firm anchoring, the directions in which the individual root ramifications grow need to be coordinated, let alone the individual avoidance of obstacles like, e.g., stones. Since an established root cannot change its shape any more, growth direction can only be achieved at the tip of the root, the apex. Currently, there is a general agreement that higher plants are not only able to receive diverse signals from the environment but that they also possess mechanisms for rapid signal transmission [4]. In fact, each root tip is able to receive information from the environment via embedded sensors; the information is then transduced and processed in the whole root system and used to direct the growth toward regions of the soil with, e.g., the best minerals and water availability. So plants can effectively process information obtained from their surroundings and can show a learning behavior which involves goal seeking, error-assessment, and memory mechanisms [5, 6, 7]. Therefore plants demonstrate to successfully reach their needs even without a conventional locomotion system. In consequence, root apices are not only sites of nutrient uptake but also sites of forward movement. During growth, plant roots may exert pressures of up to 1 MPa in order to penetrate hard soils [8]. Consequently, virtually all plants which grow in soil have evolved root caps which protect the root meristem from physical damage or abrasion by soil particles. These caps play an important role not only in protecting the root meristem from damage, but also in determining the mechanical interaction between the root and the soil, namely the mode of soil deformation and the rootsoil friction [9].

Scenario for a biomimetic plant

In the present account we focus on planetary anchoring solely without taking into consideration issues of an entire space mission such as launch requirements, space navigation, etc. It may well be assumed that the earlier stages of our proposed scenarios would be qualitatively similar to those presented to current planetary probes. However, we consider a significant change during surface approach including a rather hard - and obviously more risky - landing which would provide the probe with an initial, dynamic anchoring in the substrate similar to that of common plant seeds. Any soft landing would require an additional fixation of the probe to facilitate first penetration of the substrate by the extending roots. As we will see later, an autonomous penetration of the ground will require a closer imitation of plant roots than currently possible. A plant-robot, or eventually many plantoids, disseminated like seeds in large lands, extending their roots in the ground, could autonomously analyse the composition of soil and monitor the presence of a variety of chemical-physical parameters even in sub-surface locations. The main features of the plant-bot for sub-surface planetary exploration, are minimal power consumption and a rather compliant and friction-less penetration compared to rigid drillers which would preserve fragile samples to a better extent.

The characteristics of the substrate to be analyzed are important for the success of the penetrating principle of the roots. It is likely to be limited to a loose and fine sand and soil, while the plantoid will intuitively not able to perforate hard bedrock. Indeed, the plantoid should be able to detect and avoid such obstacles. We identified three primary space mission targets: Mars, Moon, and Asteroids. Among these targets, Mars exploration appears to be the easiest to realize, thanks to the less strict constraints. On Mars temperatures range from -87C to -5C [10], and the surface

level atmospheric pressure at the surface level averages around 0.6 kPa (i.e. less than 0.01 times the terrestrial atmosphere). The top layer of martian soil has an estimated thickness of 0.5 to 1 m and is expected to be composed of fine sand and loose soil. When reaching deeper more hard rock layers can be expected carrying stones corresponding to those of our mafurite, carbonatite, diopside and diabase [11, 12, 13]. In consequence, the roots need to be sufficiently versatile and flexible to avoid stones and hard bedrock. Even if the first layer on Mars consists in an iron oxide dust with the consistency of talcum powder there might be water ice close to the surface as was indicated by the Mars Odyssey orbiter [14] and recent findings from the US Phoenix mission [15]. Although this ice is not expected to form a rigid layer but rather be present in a grainy condition we may have to consider additional measures to facilitate penetration.

Our goals were (i) to achieve an integrative understanding of the technical aspects of plant roots as far they were relevant for our project followed by (ii) a biomimetic transfer into feasible technological concepts as well as (iii) developing a technological road-map for the 'ideal' biomimetic root. The two main aspects of this study were (i) the growth of plant roots and (ii) the control issues involved in steering of the growth directions. The cell expansion is achieved via rather slow osmotic processes which require little energy and are actuated forward with rather low friction. The several different individual roots of one plant need to individually find their way and coordinate with their neighbors. Both control within and communication between root apices are examined for a bioinspired control architecture. In the present account we report on the results of our joint work in transferring plant know how into technological concepts.

ANCHORING CAPABILITY

State of the art

Anchoring is becoming a critical aspect of planetary missions involved with in-situ exploration tasks, particularly on planets with a very low gravity, where the low weight force of the spacecraft could not be sufficient to counter-balance the reaction force generated by the terrain due to the soil probing, which could exert a significant axial push. However, anchoring systems are not well represented within the scientific literature available in the space sector. Mostly they consist of metallic thorns or nail like structures that extrude rigidly from the landers landing pads and are rammed into the ground during landing. Relevant examples of those can be found in [16] and [17]. All rigid anchor systems face the problem of performance over a longer time frame. If the soil creeps, reliable anchoring will not be granted any more. Also the sampling and probing techniques will face similar issues. Natural anchoring and sampling as exhibited by growing plants have the ability of continuous adaptation by longitudinal and radial extension, including changing of growth direction. A technical transfer of root growth may seem visionary but is desirable in terms of improved performance.

Anchoring issues

As a primary rule, the axial force generated by the anchoring process onto the terrain must be evidently lower than the weight of the spacecraft to prevent lifting it. As introduced before, the anchoring system could take advantage of the entry phase of the probe by exploiting a preliminary self-insertion into the terrain of the lower parts of the spacecraft due to impact landing on the planetary surface.This should guarantee a pre-anchoring in order to allow the extension of the robotic root and thus achieve progressively a more stable anchoring condition while eventually probing the soil for scientific investigation.

Relying on the described osmotic actuation principle, the apex would be hopefully able to steer only at the very beginning of the sandy-soil surface. Going deeper, the steering momentum requested in order to move the surrounding sand could be too large. Hence, the steering actuation should occur dynamically, that means progressively during the quasi-static forward penetration of the root. The resistance itself that the terrain will oppose to the root penetration will contribute to steer the apex into the wanted direction, producing the change in the desired direction of the penetration. This approach might actually lead to a condition where eventually only a single bending of the robotic root could occur, insufficient for a suitable soil probing, but probably enough for an anchoring purpose. In

order to evaluate the steering capability and the mentioned issues, tests in soil are definitely necessary.

Considering to push the entire root from the surface (as it happens in the Cone Penetration Tests, CPTs, in the Industrial field, where straight probes are axially pushed into the terrain for several meters), it must be observed that the penetration of a bended root would be actually even more difficult, because the pushing force will not be entirely propagated down to the apex, but only a component of the force will contribute to move the apex forward. In order to compensate this problem, the root penetration can be conceived by an initial straight insertion of several root modules into the terrain which is followed by a serial actuation of the underground modules from the upper stages down to the apex, in order to avoid to push all the already extended modules; this should decrease the problem of advancing all the root through a bended path (that means also decreasing the sleeve friction while the root is penetrating).

It must also be considered that on Mars, for instance, the gravity is about one third the gravity on Earth and the mean surface level atmospheric pressure is less than 0.01 the Earth pressure. This should be a more favorable condition to the soil penetration compared to Earth tests. On the other hand, this is a unfavorable condition regarding initial anchoring capability. Experimental trials in soils could actually simulate such a condition and demonstrate if it exists a suitable compromise between force requested for the penetration (which in turn relies on the root size considering also the exploitation of the osmotic actuation principle) and anchoring capability in order to prevent lifting of the system with a specified weight.

ACTUATION

Mechanistic understanding of root growth needs to take into account the architecture of the root growth zone. As a given region of the plant axis moves away from the apex, its growth velocity increases (the rate of elongation accelerates) until a constant limiting velocity is reached equal to the overall organ extension rate. In a rapidly growing maize root, a tissue element takes about 8 hours to move from 2 mm (the end of the meristematic zone) to 12 mm (the end of the elongation zone), with a main velocity of 3 mm/h. In physical terms, cell growth can be defined as an irreversible increase in cell volume and surface area. Plant protoplasts are characterized by an univocal structure and organization, as they are surrounded and encased by a rigid, but expandable, cell wall with elastic characteristics. The cell wall is infiltrated with water containing only a very low osmotically active amount of solutes. This situation enables the formation of a large difference in osmotic pressure ($\Delta\Pi$) between the apoplastic (outer) and the symplastic (inner) space (0.6-1.0 MPa), compensated by a hydrostatic pressure, named turgor (P), of equal value when the cell is in a fully turgid state. The cell can hence be described as a simple osmometer that can enlarge by water uptake powered by a difference in water potential ($\Delta\Psi$) between protoplastic and symplastic space.

Growth in plant roots is a result of two mechanisms: (i) cell division in the apical meristem just behind the tip, and (ii) cell elongation in a zone just behind the apex [18]. The driving force for cell elongation is an increased turgor (i.e. pressure) through water influx into the cell (Figure 1). This water influx is a result of the osmotic potential within the plant cell located in the elongation zone [19]. The water relations of expanding cells have been reviewed in detail [20]. A typical value for the vacuolar osmotic potential (equal to Π_i) inside a cell in the growing zone of an unimpeded root grown in hydroponics is around -0.7 MPa (about 7 Atm). Classically, following experiments on cell walls isolated from giant algal cells [21], cell elongation has been regarded as plastic flow of the wall material under stress [22]. Where existing soil channels are smaller than the root diameter, roots must exert a growth pressure in order to displace soil particles, overcome friction and elongate through the soil. The growth pressure σ is equal in magnitude to the soil pressure that opposes root growth. In a root tip elongating through soil, cell turgor pressure P generates the growth pressure σ, which results from the difference between P and the wall pressure W [23].

In unimpeded roots, σ is by definition zero and P is balanced by W. When roots are completely impeded and cannot elongate, σ attains a maximum value σ_{max}. Roots exert growth pressures in both radial and axial directions, but we will only
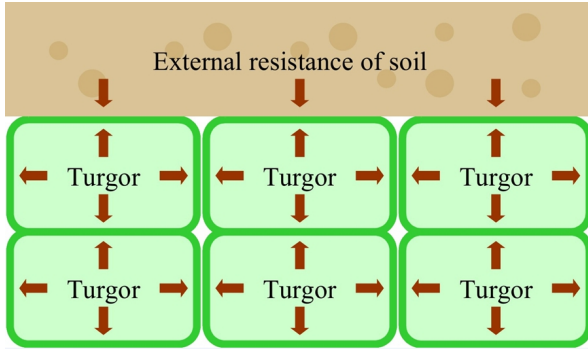
Figure 1: Schematic representation of a root growing in soil. The turgor acts against soil resistance.

deal with axial growth pressures here. When water transport into growing cells is not limiting, root elongation rate can be considered in terms of a simplified Lockhart equation [22], as modified by [23] to take account of the soil impedance:

$$R = m[W - Wc] = m[P - Wc - \sigma]$$

where R is the elongation rate, m is a cell wall extensibility coefficient, W is the wall pressure, Wc is the cell wall yield threshold, P is the turgor pressure and σ is the soil impedance (or growth pressure). As shown above, the mechanism of root cell expansion is driven by the osmotic pressure. This osmotic expansion mechanism could be successfully used to design a new class of electrochemical actuators able to fit the necessary requirements (low power, slow actuation, high force/pressure). The concept of this new electro-osmotic actuators inspired by plants will be presented in the next sections.

The theoretical working principle of the plant inspired electro-osmotic actuator is now described in detail. Figure 2 shows two cells connected through a semi-permeable membrane. Each cell has a metallic electrode (M and N) immersed in a water solution of own ions (M^+ and N^+, respectively molal concentration c_{M^+} and c_{N^+}) in presence of a counter-ion (X^-), required for the electroneutrality of the solution. If the concentration of the two cells is different, an osmotic pressure is generated across the semi-permeable membrane. In this case the osmotic pressure Π is given by the Van tHoffs law [24]:

$$\Pi = \Phi \left(c_{M^+} - c_{N^+} \right) R \cdot T$$

where R is the gas constant ($0.082 \, l \cdot atm \cdot mol^{-1}$), T the temperature (in Kelvin) and σ is the molal osmotic coefficient, a coefficient that takes into account the non-ideality of the solution. On the base of the equation (2) it is possible to evaluate the theoretical pressure achievable by using the osmotic mechanism. Considering a difference of electrolytic concentrations between the two cells of 1M (a realistic achievable concentration) and considering the molal osmotic coefficient $\sigma = 1$, we obtain a pressure of about 2.5MPa (24 Atm). The force that can be exploited by this pressure is obviously essentially related to the geometry and dimensions of the transduction mechanism. Few examples of devices that use pure osmotic actuation mechanism are available in literature [25].

To control the displacements and the forces generated by such kind of osmotic actuator it is necessary to control the ion concentrations on the cells. This goal can be achieved by using electrochemical reaction. If the membrane that connects the two cells allows the passage of some kind of ions (not simply a semi-permeable membrane), thus the cells can work as a battery (it can generate an electrical current) or conversely work as electrolytic cells (applying a suitable external voltage).

The two reduction semi-reactions involved in the process are:

$$M^+ + e^- \rightarrow M$$
$$N^+ + e^- \rightarrow N$$
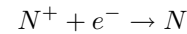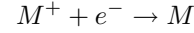
The electric potential across the two electrodes ΔE is given by the Nernst equation:

$$\begin{aligned} \Delta E &= E_M - E_N \\ &= \left(E_M^0 - E_N^0 \right) + \frac{R \cdot T}{F} ln \left([c_{M^+}] / [c_{N^+}] \right) \end{aligned}$$

where E_M^0 and E_N^0 are the semi-reaction standard red-ox potentials, and F is the Faraday constant ($F = 96,485.34 \, s \cdot A \cdot mol^{-1}$). Providing a suitable current to the cells it is possible to control the concentrations of the electrolytes. The electrical potential needed to induce a current in the cells is in the order of few Volts (at considered concentrations). The induced variation of electrolyte concentration within a cell, after application of a current I for a time t, is given by the following equation:
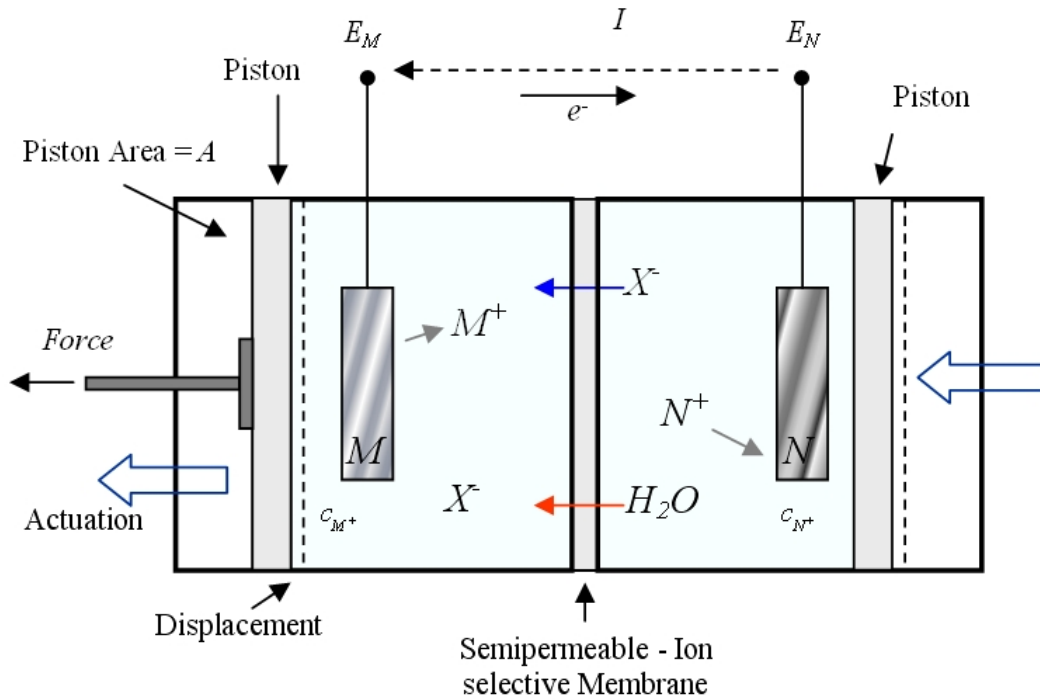
$$c_{M^+}(t) - c_{M^+}(0) = \frac{I \cdot t}{F \cdot V}$$

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Figure 2: Working principle of a electro-osmotic actuator.

where V is the volume of the cell. It is important to underline that in front of the variation of concentration of the active electrolytic chemical species (in this case the cations M^+ and $^+$) due to the red-ox process, the ionic transport of counter-ions (in this case X^-) must be allowed (otherwise electrode gets polarized), by means of a ion selective membrane. Clearly the active ionic species must be blocked by this membrane otherwise a net variation of concentration is not achievable.

Since the underlying physico-chemical processes are rather well understood we were able to identify candidate component for a hard-ware realisation of an electro-osmotic actuator: Two chemicals - $Pb(ClO4)_2$ or in alternative $PbSO_4$ - can be used to provide the relevant ions to drive the process. However, we were not able to identify a membrane that would combine ion-selectivity and osmotic permeability at the same time. Hence, composite membranes had to be evaluated. In this context, we performed some very preliminary experiments to monitor the performances. In a first set of experiments performed on these membranes we have obtained that with 2 chambers of 15 x 60 x 60 mm, 1

molar solution of NaCl in H_2O and 12.5 mm^2 exchange surface, the highest pressure has been obtained with Cellulose Acetate RO CE membrane, 11 Atm reached in 3 hours. This pressure is comparable with the growing pressure generated by the plant roots. Similar test will be performed with lead in order to evaluate the maximum pressures obtainable with a controlled process. In combination with anionic exchange membranes we achieved a satisfactory selectivity response and relatively low resistance (allowing reasonable ionic flows), making them useful for our application.

CONTROL

The root system, which is the plant organ devoted to soil exploration, is composed by thousands of root tips or apices. Each apex receives information from the environment via embedded sensors and uses it to direct growth toward soil regions with high mineral and water availability. The transition zone of the root apex - situated between division and elongation zone - is able to detect more than 10

chemical and physical environmental parameters. In this zone, the cells exhibit a unique cytoarchitecture with centralised nuclei surrounded by perinuclear microtubules radiating toward the cell periphery. This particular configuration should be suited for the perception of external stimuli and a subsequent transmission to the nuclei. The transition zone is also regarded as the location of information processing, decision taking, and information storage due to its high energy consumption in form of ATP.

The growth of root tissue relies on the establishment of cellular and sub-cellular asymmetries. The formation of the real cell shape and the positioning of molecules in the intracellular space commonly involve a persistent directional orientation along an axis, named cell polarity. Polar transport of auxin is directly linked as a signal to the regulation of both growth and polarity in the plants. As the plant body is shaped in response to numerous environmental stimuli (i.e. light and gravity; [26, 27], these factors are able to influence the transport of auxin in a way that this hormone is delivered to tissues induced to grow via the establishment of auxin gradients, transport and response. Auxin is transported across the whole plant body via effective cell-cell transport mechanisms involving both the symplast and the apoplast. Cellular auxin influx and efflux, and the mechanisms that mediate the delivery and removal of potential polar auxin transport components from the plasma membrane, remain still open and discussed. For example, it is not clear why auxin bypasses the cytoplasmatic channels of the plasmodesmata crossing through the apoplast, as their diameter could easily accommodate several auxin molecules. This suggests the presence of an active mechanism that prevents auxin entering the plasmodesmata [28] and implies a functional benefit for including an apoplastic step in the polar transport of auxin. Transcellular auxin transport is accomplished via a poorly understood vesicle-based process that involves the putative auxin transporters, or transport facilitators, recycling between the plasma membrane and the endosomes. Active auxin transport mediates cellular auxin concentration and is therefore a crucial component in the coordination of plant development. However, the specific relationship between auxin signaling and auxin transport is still quite unknown.

Plants, along their evolution, have had to face and solve a variety of problems to survive: developing support structures, creating a system of transport of water and nutrients through the whole organism, protecting the delicate reproductive organs, assuring the reproduction in the most convenient period of the year, improving the mechanisms of adaptation to the variable climatic conditions etc. All these needs has led to large modifications in metabolism and has brought to the acquisition of sensorial structures to set up a precise biological clock necessary to guarantee the constant monitoring of the surrounding situation to acclimatize them. Plants can sense gravity, temperature, light quality and direction, etc., and if necessary they can act consequently. Plants feed themselves, breathe, fight the infections, in some cases generate symbiosis with fungi and bacteria and communicate with them. They live in continuous competition both with environmental agents and with other plants for the conquest of light, space and nourishing substances, and all those necessary elements to their survival. They also live in continuous competition with other predator organisms, fungi, bacteria or animals. When circumstances become unfavorable for optimal growth and development of animals, they can respond accordingly by moving to a more favorable environment. Plants are not afforded this luxury. Due to their sessile nature, plants are forced to make the most of their immediate surroundings, which means adapting to an ever-changing environment [29]. So they have been adapted to perceive and react to adverse situations with varies useful movements to the survival. Darwin noted that plants had a tendency to sense their environment so as to orient themselves for optimal growth and development, and he dedicated part of his studies to vegetal biology publishing with his son Francis a fascinating book "The Power of Movement in Plant" [30] in which he encloses many interesting observations on plant life with special interest in movement. The Darwins studied the two great categories of "movements in the plants": "tropisms (directional movements in answer to external directional stimuli) and "nastic movements" (movements in answer to external stimuli, but independent to their direction). Plants are constantly being bombarded with changes in their environment. Temperature fluctuations, not enough light or water content in the soil, are just a

few of the factors to which plants must be able to respond. Moreover, plants must respond to physical forces of nature such as gravity or touch stimulation. Over evolutionary time, plants have adapted to their surroundings with a high degree of plasticity, affording them the ability to respond to ever-changing conditions that provide constant stimulation. Plant tropisms are operationally defined as differential growth responses that reorient plant organs in response to direction of physical stimuli. An example of tropism regards the perception of gravity, also called Gravitropism. Phototropism is the directional response in answer to a luminous source. Tropisms can be negative, such as a stem bending away from a gravity stimulation [31], or they can be positive, as in a stem bending toward a light stimulation [29] while example of nastic movements are the closing leaves, modified as fly-trap, of *Dionea muscipola*, the fast closing of the composed leaves of *Mimosa pudica* to a tactile stimulus, or the closing leaves of many leguminous during night (nictinastic movements). Darwin studied also another type of movement, oscillating and rhythmic, called "circumnutation": plants, during their growth, perform circular movements around a central axis [32]. Nearly all the plants present this growing movement, however it turns out to be more obvious in some species rather than in others, such as climbing plants [33, 34]. Therefore tropisms are that group of reaction mechanisms that the plant acts in relation to directional stimuli. The most known and studied are: phototropism the answer to light; gravitropism the answer to gravity; electrotropism the answer to an electric field, hydrotropism the answer to a gradient of water in soil.

In the earth gravitational field the roots grow toward the bottom for better supplying water and nutrients (gravitropism). As gravity is a physical force which only act on masses, several organelles or particles which are denser or lighter than the cytoplasm can be involved in gravity sensing. The stages of gravitropism in plants can be divided into: perception of the signal, transduction, and response [35]. In roots, gravity perception occurs in the root tip and the response (differential growth) in the zone of elongation, involving the plant growth hormone auxin. In higher plants, there is a temporal and spatial separation between perception and response, and the signal must be transmitted over a relatively large distance. Two models are proposed

for gravity perception. (1) The starch-statolith hypothesis as shown in Figure 3 proposes that perception is mediated by dense organelles (statoliths, amyloplasts located in the root tip cells). (2) The protoplast pressure hypothesis suggests that the entire mass of the cytoplasm participates in perception. The mechanism through which the plant transforms the indication of cell position into a biochemical message is still under discussion. An important question in sensor physiology is the determination of the threshold dose of a stimulus in order to provoke the reaction of the plant organ. For the gravireaction of plant roots, it has been noticed that gravitational stimuli which last 1 s (perception time) can be actively perceived by plant roots, but one single stimulus is not sufficient to determine any organ response. So, a minimum time of continuous stimulus must occur (presentation time). When a root is subjected to a change of orientation in the gravitational field, the stimulus is perceived in less than 1 s. However, this 1 s stimulus is not sufficient to induce a gravitropic response it must be repeated about ten times (or the stimulation must last 10 s) to initiate an asymmetrical signal within the statocytes (transduction phase). This leads to a downward lateral movement of the growth hormone auxin (transmission phase) that is the cause of the differential growth occurring after a latent time of 10 min. The four phases are represented in sequence but perception, transduction and transmission can persist for the whole period of the gravitropic reaction.

Plantoid controller

As a mechatronic system, the robot will be built on a modular scheme. The plantoid can be divided in two major sections: a first part, which corresponds to the trunk and leaves and it is the upper section of the robot, located out of the soil; a second part, which represents the roots, able to move in the soil. In particular, the upper part of the plantoid aims at (i) acquiring energy from the sun for the working of the robot, (ii) storing the energy, (iii) transmitting the data concerning the soil analysis to a remote station, (iv) managing the plant at high level, and (v) eventually storing the fuel (water or other) of the osmotic process for root growth.

The energy is collected by solar panel; the surface of this panel is quite small (depending on the
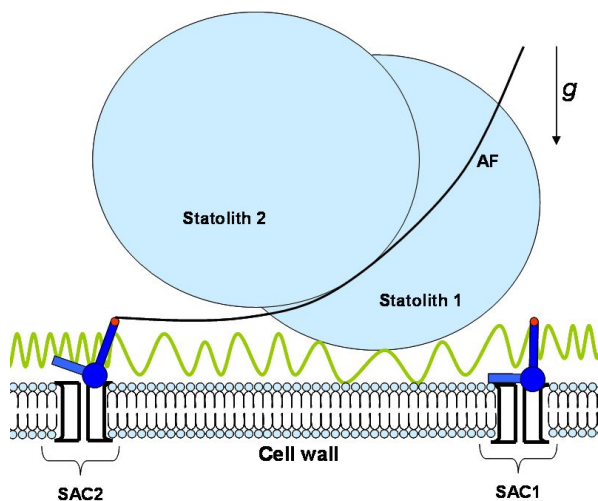
Figure 3: Functional scheme of mechanosensing in root statocytes. The statoliths are able to open the Stretch-Activated Ca^{2+} channels (SACs) through an exerted tension on actin filaments (AF) or a pressure on bridging filaments (BF) that link SACs. (Modified from [35])

solar radiation on the planet) because the power required by the osmotic actuators is very limited. In particular, for the root apex the current consumption (osmotic actuator + microcontroller and sensors) can be estimated around few mA with a supply voltage of few volts. For the entire root, e.g., composed of 10 modules, it can be roughly estimated a power consumption on the order of tens of mW. The major consumption comes from the transmission block; nevertheless, the data to be sent are not many (the plant movement is very slow and, consequently, the soil analyzed is limited and the data to be acquired are few) and they can be transmitted in a unique solution during the hour of major solar irradiance. The power consumption depends on the type of transmission. For example, the power necessary to transmit to a base located on the planet surface is different from the power necessary to transmit to an orbiting spacecraft. However, these issues are well known in the space field. The energy collected by the solar panels is stored in a battery in order to have energy during the absence of solar radiation. Moreover in the trunk of the robot, there are located also the actuators for commanding the pull out of the

solar panels and the tank of fuel for the osmotic process. These components are managed by a microcontroller, which performs several functions:

- It controls the high level tasks of the plantoid;

- it collects the data coming from the roots and it uses them to indicate to the roots the portion of soil that must be analyzed;

- it manages the transmission module;

- it commands the actuators for the solar panels;

- it manages the osmotic tank in order to indicate to the roots when growing.
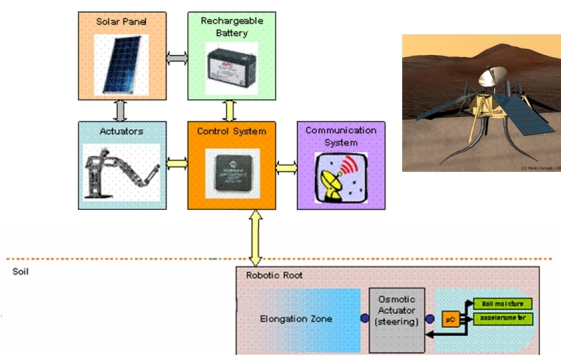

Figure 4: Elements of the plantoid involved in operating the technical roots.

The lower part of the plantoid is located into the soil and it is composed by the robotic roots. The plantoid roots will be able to grow following different stimuli, such as gravity direction, in order to explore the environment in terms of presence of a variety of chemical-physical parameters and life signatures. Each root is formed by an apex that comprises sensors and the control part electrically connected to the main microcontroller in the plant body, and by an elongation zone that connects mechanically the apex and the trunk of the plantoid. Each apex embeds a microcontroller module for the emulation of the roots behavior through the local implementation of networks using as models the real apexes behavior. By imitating the plants strategy, the robot will move slowly, exploring efficiently the environment and showing high actuation forces and low power consumption. The plantoid apex will grow and move into the ground
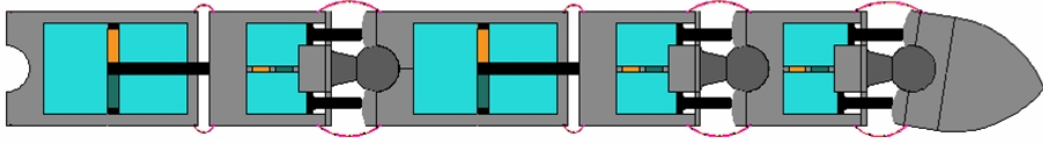
Figure 5: Schematic bi-dimensional overview of the technical root-concept at its current state: penetration is conceived by the use of osmotic axial piston-like modules that are connected by means of controlled steering stages.

through the new electrochemical actuators, based on the variation of the osmotic pressure in a liquid, controlled by small electrical signal application (electro-osmotic actuators). These actuators allow a root movement on the plant time scale, applying relative high forces with low power consumption. The plantoid will be able to expand and actuate its roots, implementing *de facto* a biomimetic growing mechanism. All the roots of the plants are then connected to the central body to realize a network that drives the growing of the roots in preferential directions, driven by the information acquired by the sensors on the apices.

Plantoid sensors

As already described, the roots and in particular the root apexes reply to the changes in the environment through mechanisms that are known as tropisms. In detail, the apex has sensors for the gravity (statolith), for the soil moisture and chemicals, which produce respectively gravitropism, hydrotropism and chemotropism. In order to imitate the plant behavior, the following components are considered (compare Figure 4):

- an accelerometer to replicate the capability of the root to follow the gravity;

- a soil moisture sensor to follow the possible gradient of humidity in the soil;

- a microcontroller to realize the distributed control of the plant (every apex is an independent unit);

- a number of actuators (osmotic) for the steering and the penetration of the root in to the soil;

- other sensors to perform chemical analysis of the soil.

CONCLUSIONS

The present concept of a technical root - integrated into a plant-robot called plantoid - mirrors a number of technical features found in plants (Fig. 5). With some initial insertion, the plantoid can extend its roots and drive them slowly into the ground. The energy delivered by the solar modules is sufficient to drive the osmotic actuators. The sequential arrangement of the actuators allows for a reduced friction when pushing the roots into the soil. Similarly actuated joints provide compliance. The controller is sufficiently small to be integrated into the tip of the root. At this first attempt to mimic roots in a technical concept these feature are unique. So far we are aware of only one other attempt to mimic roots for planetary anchoring [36]. However, the approach differs considerably as it integrates the biological technologies far less. In the future the here presented concept awaits experimental evaluation which will definitely lead to further optimization.

But the visual comparison between the thin and numerous roots of plants and the rather bulky design of our technical root already illustrates the long way development has yet to go. The most obvious advantage of plants is their cellular growth which is facilitated by the ion-selective and expandable cell membrane. Replicating such a compliant and still powerful device will remain a challenge for the next decade. In consequence, the technical root will also not achieve lateral growth which is important for continuously counteracting any creeping of the substrate as a consequence of, e.g., external loads.

In addition to that, the cellular growth of root tissue allows for almost friction free actuation. Our technical concept works rather like an inverted telescope and hence displays reduced friction but not to the extent a plant root is able to achieve. The

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simplicity of the plant sensors and control architecture is again unmatched and more research on these sensors is necessary before they are completely understood and await technical transfer. However, the potential of technical roots is obvious and if biomimetic research is continued we might one day make use of these roots not only to anchor, but also to exploit existing resources for growth and external use.

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