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PAPER

A perspective on plant robotics: from bioinspiration to hybrid systems

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Abstract

As miscellaneous as the Plant Kingdom is, correspondingly diverse are the opportunities for taking inspiration from plants for innovations in science and engineering. Especially in robotics, properties like growth, adaptation to environments, ingenious materials, sustainability, and energy-effectiveness of plants provide an extremely rich source of inspiration to develop new technologies—and many of them are still in the beginning of being discovered. In the last decade, researchers have begun to reproduce complex plant functions leading to functionality that goes far beyond conventional robotics and this includes sustainability, resource saving, and eco-friendliness. This perspective drawn by specialists in different related disciplines provides a snapshot from the last decade of research in the field and draws conclusions on the current challenges, unanswered questions on plant functions, plant-inspired robots, bioinspired materials, and plant-hybrid systems looking ahead to the future of these research fields.

1. Introduction

Taking inspiration from nature is crucial for developing sustainable technology which is capable of integrating instead of unbalancing the processes that each life and all matter on our planet is dependent on. The Plant Kingdom has been and will remain a crucial source of inspiration. It spans over at least 370 000 species [1]. Indeed a single plant species offers multi-fold mechanisms and materials interesting for bioinspiration from roots to leaves, seeds to flowers, and many more [2, 3]. Moreover, plants respond in a specific and distinct manner to stimuli from their environment. Figure 1 summarizes the key features that are interesting for plant inspired technologies (growth, actuation, autonomy, energy efficiency, sustainability). Moreover, it summarizes external stimuli that cause responses in plants and plant-inspired robotics and lists the so far most-mimicked plant organs, inspirational for technological devices. Figure 2 will then show examples for bioinspired artefacts mimicking these key features as further described in the next sections. One of the most important characteristics is that plants are sessile organisms and do not change their position much beyond 100–200 m, except through propagation (e.g. spreading of seeds) and locally through growth above and beyond ground. That, however, does not imply that plants do not move [4]. Moreover, it implies that plants must have developed strategies to interact with their direct environment with an efficient and rich set of features that artificial technology and robotics yet do not always have. Instead, the collective catalogue of movements observed in plants operate on various timescales from extremely fast (milliseconds) to slow (days/months) [5]. The movements result from mechanisms like pre-programmed materials released upon trigger, water-responsive structures, osmosis,

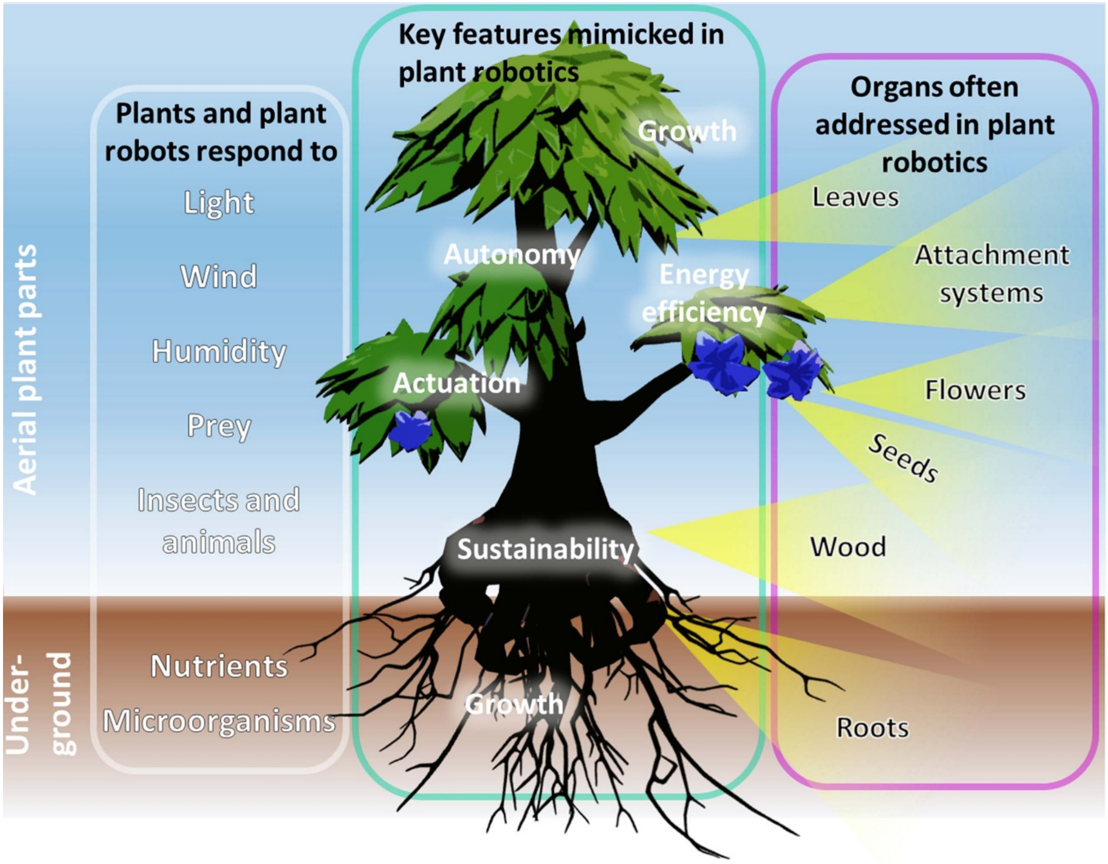

Figure 1. Overview of various plant features robotics and technology is already and could be inspired from: plants have aerial and underground parts, they respond to multiple stimulants through adaptation, materials, actuation. Several plant organs differing structurally from species to species are inspiration for bioinspired and biohybrid technology. Key features for inspiration are growth, autonomy, actuation, energy efficiency, and their intrinsic sustainability.

interactions with heat, light, stiffness-changes, and especially growth. This catalogue of functions is supplemented with further functionality for interacting with their environments, specialized surfaces, biodegradation, and adaptation. Plants are complex organisms with intricate biochemistry, environmental sensing and stimuli-response mechanisms, and organism-organism interactions. Yet, even the individual components of these biochemical, living material-based, and mechanistic actions provide extremely rich sources of inspiration to develop structures, materials, and mechanisms to realize complex robotic systems.

Herein, we gathered examples and perspectives of plant-inspired technology and we highlight mechanisms that will be important in the near future. This perspective focuses on growth, autonomy, and actuation, but also on plant-inspired materials and plant-hybrid systems which use living plants as part of high-tech devices to replace artificial components. We show, that in both plant-inspired materials and plant-hybrids, it is possible to go beyond the common and conventional and obtain new functionalities. It is also possible to reach excellent sustainability during operation—a feature displayed elegantly in living organisms.

2. Plant-inspired growth

Primary growth, from meristematic apical cell division and elongation is an essential intrinsic characteristic of all plant species and a requirement to develop organs for expansion and propagation. Some organs never stop growing. The structural and functional properties of plant bodies, and their strategies to move across unknown and challenging environments through adaptive growth paths make plants a unique, novel model for robotics. Plants explore and colonize their surroundings, overtaking obstacles and moving in complex conditions, e.g. roots moving in the soil or plant bodies climbing on rough, uneven surfaces, or over unstructured barriers. They adapt to many different chemical and physical signals from the outside. In response, they display a series of growth-driven movements and decision-making strategies whose engineering translation has proven to enable new abilities for improved motion and exploration of plant-inspired robots. For example, investigations on a peculiar growth-driven movement observed in plant roots, i.e. circumnutation, demonstrate its role in optimizing soil penetration [6]. Primary growth has been imitated in artificial implements by various strategies, including 3D printing [7, 8] (examples in figures 2(a) and (b)), skin eversion [9, 10] (example in figure 2(c)), pressurized elongating tubes [11], or chain locking mechanisms [12]. Solutions equipped with an exploratory head typically demonstrated their effectiveness when moving on the ground [13, 14] due to insufficient structural properties for sustaining tip weight. In other cases, exploration is limited by protruding elements that can interfere in the presence of obstacles and in narrow spaces, locking the moving head [7, 12]. Solutions capable of 3D-spanned motion are currently limited by their low manoeuvrability [7, 8]. However, in all strategies, apical propagation of the robot occurs significantly faster than in plants and, compared to other strategies of navigation in unstructured environments, provide the robots with more freedom to develop new structures on-demand following a previously grown element. Yet, a disadvantage is that the new material needs to be transported to the tip to be used for growing, at least until there are strategies to harvest materials directly from the environment.

The extension of the body through apical growth adopted by plants has been verified to facilitate soil penetration in artificial penetrometers imitating the addition of new material at the tip via embedded additive manufacturing techniques [8, 15] while enabling passive body shaping (figure 2(a)) [16] and to be a promising alternative to animal locomotion for navigation in above ground applicative scenarios [14, 17]. Strategies of self-orientation and environmentally-driven growth have been translated into effective explorative control strategies for these plant-inspired autonomous systems [18, 19]. Plants are viable models for engineering novel artificial systems, enabling new abilities for dynamic adaptation, such as morphing and growing, helping to reduce forces and energy employment, e.g. in digging tasks for artificial penetration devices or cluttered environments exploration.

Among many options, additive manufacturing processes integrated in the robot's body can offer promising versatility in terms of on-demand adaptation and full 3D environment exploration, with the advantage of using off-the-shelf, cheap materials for growing the robot's body. Yet, several technological challenges are intrinsically present, especially in miniaturized 3D printing technologies and when operating autonomously in unpredictable and uncontrollable conditions. The main challenge ahead includes the embodiment of sensing and actuation in 3D-printable functional materials to empower bodies of growing robots with exteroceptive properties and distributed movements. Future robots will not need a pre-defined, static design but adaptable bodies that can morph and purposefully adapt for enhanced robot-environment interactions. The realization of such a system could open up new frontiers in the autonomy of robots navigating unstructured environments.

3. Plant-inspired continuum robots

3.1. Vine-inspired tendrils

Growth is an intrinsic need for organ development in all plant species and some species are particularly interesting for robotics applications. Vines are inspirational for continuum (continuous backbone) robotics not only in their ability to grow [10, 20], but also their additional wide variety of approaches to environmental attachment. The ability of vines to attach to stable features of the environment (walls, other plants, etc) allows them to establish contact points between the support and the plant and friction that helps to achieve vertical growth [21]. For the plant, the balance between energy expenditure and energy gain when climbing on a support is essential. Different attachment strategies such as tendril climbing, twining, hook climbing, may have different energy expenditure and for example, tendrils and twining consume more adenosine triphosphate than hook climbing [22]. Partially, these concepts have been translated into robotics although detailed analysis from an energetic point of view could be interesting. Work in the development of thin continuum robots [23, 24] has demonstrated the use of passive 'prickles' [25] and actively coiling tendrils (figure 2(d)) [26, 27] to attach to environmental features. The mechanically stable tips of the micron-sized occurring in some plants like the leaf-climber *Galium aparine* have also been mimicked as attachment systems (figure 2(e)) with additional functions as detailed later. Such attachment for thin robots—as with vines—stabilizes their thin structures at the point of connection supporting their more distal parts for navigation and inspection tasks. However, robotic analogues of the numerous other strategies vines use for attachment (e.g. adhesives) have yet to be explored.

3.2. Tree- and root-inspired robots

Beyond vines, plants serve as examples for numerous alternative continuum robot structures [28]. Novel robot forms developed thus far include variable topology 'branching' robots, featuring a continuum 'trunk' with retractable continuum 'branches' [29], and continuum root-inspired robots [30]. The interaction of plant roots with their environment offers a novel form for continuum robot/environment interaction [15]. The integration of continuum robotics with plant-inspired growth has increased robot workspace by body lengthening from the tip and reversible movements [31]. Design and control complexity, especially of long structures are current

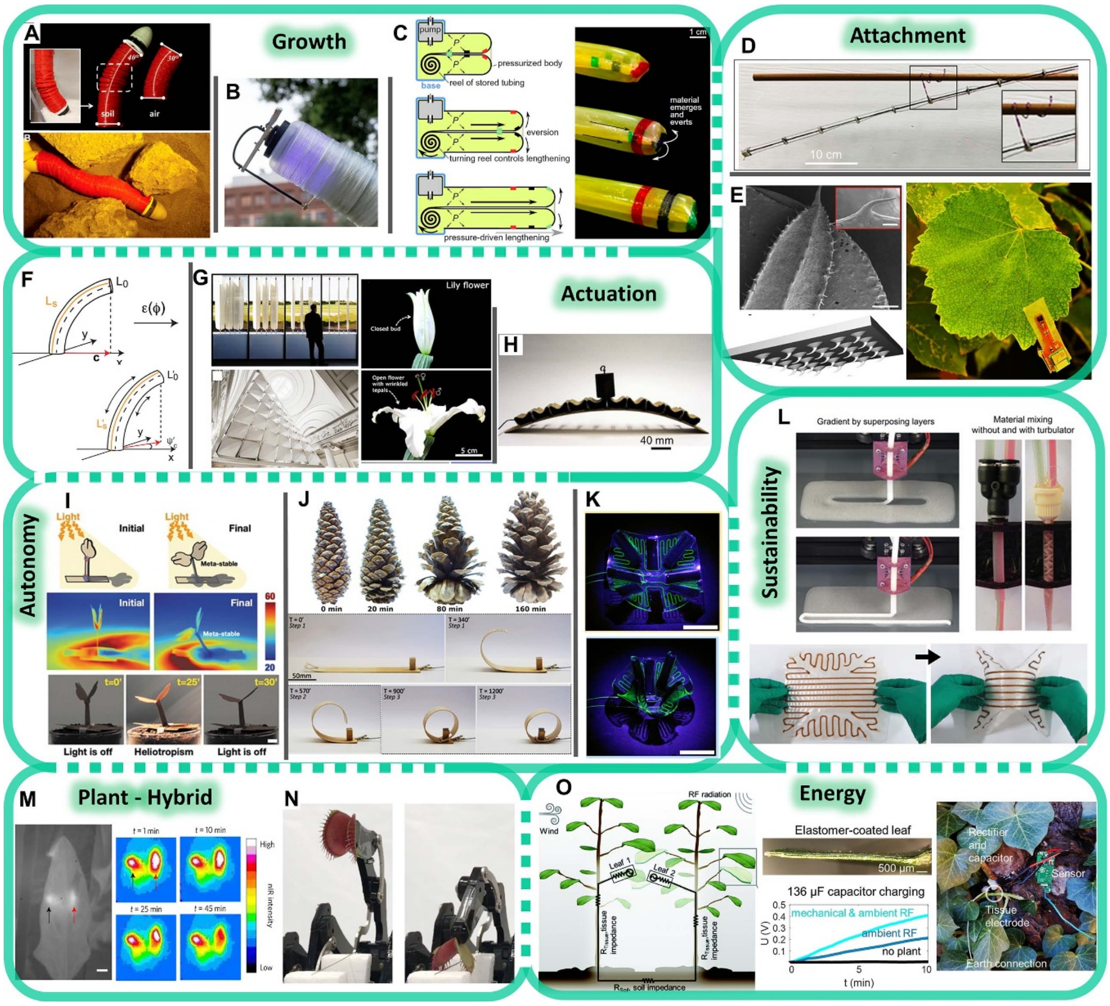

Figure 2. Examples for plant inspired machines, materials, and plant-hybrid systems. The turquois boxes represent key features addressed in the examples; the dashed lines indicate that concepts are often connected to multiple target features such as of the neighboring box. (A) A robotic root growing and navigating in unstructured environments by 3D-printing its own body and passive morphological adaptation for obstacle avoidance (Reproduced from [16]. © Ali Sadeghi *et al* 2019; Published by Mary Ann Liebert, Inc. CC BY-NC 4.0). (B) Robot extruding fiberglass thread and UV-curing resin obtaining growth-like behavior (Reproduced from [7], with permission from Springer Nature). (C) Growth-like behavior in a robot through pressure-driven eversion (From [9]. Reprinted with permission from AAAS). (D) Robot tendril on searcher grasping environment (Reproduced from [27]. CC BY 4.0). (E) Micro-sized hooks of climber *Galium aparine* inspired a miniature anchoring system for attaching sensors to leaves and for the delivery of molecules (Reproduced from [32]. CC BY 4.0). (F) Approximation of a shoot as 3D model using cylindrical coordinates to obtain a mathematical description of the kinematics of plant nutation based on the interplay between geometry and differential growth (Reproduced from [33]. CC BY 4.0). (G) Motile biomimetic facade shading elements inspired by the pollination mechanism of the bird-of-paradise flower (*S. reginae*). On the right: the lily cultivar *Lilium* 'Casa Blanca' shows growth-based edge actuation of its petals (Reproduced with permission from [34]. © The Author(s) 2020. Published by Oxford University Press on behalf of the Society for Integrative and Comparative Biology. All rights reserved. For permissions please email: journals.permissions@oup.com). (H) Pneumatic cellular actuator inspired by the bulliform cells of *S. nitida* (Reproduced with permission from [35]. © 2020 The Author(s)). (I) Self-regulated elevation tracking through material feedback in a plant displaying both heliotropism and nyctinasty (Reproduced from [36]. Copyright 2020, Mary Ann Liebert, Inc., publishers). (J) The hydration-dependent sequential motion in pine cones inspired a wood-based 4D-printed prototype with sequential inter-locking motion (Reproduced from [37]. © The Author(s). Published by IOP Publishing Ltd. CC BY 4.0). (K) Leaf-inspired multi-stimuli responsive microfluidic device encapsulating a photosynthetic reaction (From [38]. © The Authors, some rights reserved; exclusive licensee AAAS. Distributed under a CC BY-NC 4.0 license. Reprinted with permission from AAAS). (L) Printing of plant-based biodegradable functionally graded materials with programmable deformation (From [39]. © The Authors, some rights reserved; exclusive licensee AAAS. Distributed under a CC BY-NC 4.0 license. Reprinted with permission from AAAS). (M) Plant-hybrid sensing platform: a living plant acts as pre-concentrator for analytes detected with carbon nanotubes. Bright-field image of spinach plant leaf and false-colored time-lapse pictures in response to nitroaromatics sensing (Reproduced from [40], with permission from Springer Nature). (N) Integration of a Venus flytrap leaf with a robotic hand that enables grasping (Reproduced from [41], with permission from Springer Nature). (O) Living plants for multisource energy harvesting: modification of the plant leaves with a thin silicone elastomer layer enables a mechanical wind energy harvesting based on triboelectric effect. At the same time, the ion-conductive tissue of the plant can be used as antenna for radiofrequency energy harvesting able to power a wireless sensing platform (Reproduced from [42]. CC BY 3.0).

challenges. Growth is a form of actuation and the intrinsic movements of plants together with attachment solutions and mechanical properties of the tissue are mechanically different from animal, human, or microorganism motion. This provides a unique opportunity for obtaining solutions, not only in robotics but also architecture and general autonomous adaptive systems.

4. Understanding plant functions for growing robots

Deriving plant-inspired technologies requires exploring and understanding the multifaceted and interlaced developments performed by plants that can be classified in sensing, response, movements, material, organ development, and especially adaptation. However, plant-inspiration provides more unique features based on the interaction and liaison of development and external/environmental situation the body has to adapt to.

Current state-of-the art robots boast highly developed control systems, allowing intricate motor skills such as posture (ranging from somersaults to regaining balance from external forces), complex grasping and manipulation, and decision-making—all of which are at the basis of any robotic function. However, while these control systems are extremely advanced, they cannot be adapted, for example, to a growing robot. The reason lies in the fact that the basis for these control systems is the assumption that the structure of the robot is fixed, and usually also completely known. This assumption means that the system can predict, for example, the expected forces experienced by a specific joint—and any deviations can be interpreted as an external force, which the robot can then counter. This is not the case in a growing robot, where the structure continually changes over the course of time, and furthermore in an *a priori* unpredictable manner, since its form is a result of external stimuli and the possible ability of the robot (and the plant) to perceive itself (see section 2). This fundamental gap necessitates revisiting the way basic functions are thought of in the context of growing robots, and requires study of how plant systems tackle this challenge.

Quantitative studies of plant behavior, viewed as an input-output system amenable to plant-inspired robotics [43, 44] are gaining focus in recent years, as part of the nascent field of plant behavior. One example is the pivotal work by Bastein *et al* [45], who showed that posture control in a growing organ is attained by combining gravitropism, where plants sense the direction of gravity, and proprioception, sensing the local curvature and resisting overbending. They formulated this understanding within an experimentally informed mathematical model. The model successfully describes the posture control involved in the growth dynamics of an organ. Later, further generalizations provided descriptions of goal-directed movements (tropisms) as well as search movements/actuation (the intrinsic periodic movements called circumnutations), in three-dimensions (see also figure 2(f)) [33, 46–49]. Another layer of complexity comes from the inclusion of memory, based on the observations that plants do not respond instantaneously, but rather to a history within tropic responses [50, 51]. Memory provides the framework for basic behavioral processes, allowing to integrate stimuli, compare stimuli over time, and at the basis of decision-making—to name a few functions. A current bottleneck is the still limited availability of materials and structures that could enable these functions reliably in artificial matter. Realizing robotic functionality of higher complexity still strongly relies on developing mechanisms like actuation, materials which allow for sensing and memory, and new sensory and responsive systems that can be combined, controlled and integrated in the same sustainable way plants are able to do it.

5. Plant-inspired actuators

Looking deeper into the collection of actuations occurring in plants on different timescales and those which have recently been translated into technology is crucial in analyzing the potential and perspective of plant-inspired robotics. Indeed, although plants are sedentary organisms, they perform a variety of movements. These movements are driven or triggered by cell growth, osmotic pressures (e.g. turgor pressure), desiccation and rehydration, release of inner prestresses or by external influences like touch or contact with a pollinator [34, 52, 53]. Thereby plants can perform nastic, tropistic movements as well as crawling, bending, digging, growing and even snapping [34, 52, 53] that inspired, for example, mechanisms for façade shading structures (figure 2(g)).

The abstraction of the underlying principles enables plant-inspired robots to move. To implement nastic movements, which are still observable in fossil scales of pine cone [34, 54], hygroscopic materials [55] and hydrogels are used in engineering [56–58]. Correa *et al* [34, 59, 60] and Cheng *et al* [37, 61–63] use moisture-responsive swelling materials in their systems to demonstrate adaptive shading and self-erecting structures. Plant and especially root growth has inspired various growing robots, which use material deposition (as in 3D printing) [8, 64–66] or pneumatic expanding systems to move, grow, burrow, and navigate [9, 17, 26, 67]. Expanding bulliform cells have inspired, e.g. pneumatically driven bending units for shading in architecture [35]. The structure is shown in figure 2(h). Pneumatics and hydrogels are also used to implement the snapping of traps of carnivorous plants in artificial Venus flytraps [68, 69]. In case of the Venus Flyflap hydrogels are paired with shape memory polymer materials to generate a material imminent decision making in which only after two stimuli the snapping is triggered [68, 69]. Other actuators used in artificial Venus flytraps are magnets [70, 71], electrically driven ionic polymer–metal composites (IPMCs) and dielectric elastomers (DEAs) [72, 73], thermo-responsive shape memory alloys [74] and liquid crystalline elastomers (LCEs) [75, 76]. LCEs are also used to integrate phototropism into plant robots, as these materials respond to light by changing shape [75–77]. Hydrogels can be used to create movement in response to heat and light to create heliotropism or nyctinastic motions [78]. Climbing robots are equipped with tendrils that enable gripping, climbing anchoring. They grow and twine like the biological models using osmotic actuators, pneumatic cushions or hydrogels [9, 17, 26, 27, 67, 78–80].

A clear advantage of the different actuators is that being capable of transferring plant actuation principles into technological solutions generates different functional, more sustainable, and more intrinsically aesthetic features (such as shading elements in figure 2(g)). A current disadvantage is, although these systems are able to grow, move and react to their environment, the functional resilience and robustness of plants is still lacking in some of the artificial actuators—note even fossilized conifer seed scale still move in response to water. This requires improvements in materials actuation capability and responsiveness. Plant inspired actuation systems in the next decade will also have to tackle the question of autonomy and sustainability, as evermore systems require sustainable energy sources and materials. Plants can inspire such systems, as they are able to harvest solar energy from the environment, store it chemically and distribute this energy through their systems. If materials systems for actuators would be compartmentalized and outfitted with a self-replenishing energy source (e.g. chemical storage of solar energy); one could achieve actuators that power themselves by converting chemical fuel into energy or mechanical movement.

6. Autonomy in plant-inspired systems

Indeed, the main features that differ robots from ordinary machines are programmability and autonomy. In animal-inspired robotics, autonomy [81, 82] is related to freedom in locomotion, and therefore untethering is usually taken as the first target in autonomous robots [83–85]. In general, robots functioning without the intervention of an external controller and not physically anchored to an external energy source can be called autonomous. For plant robots, one can picture autonomy as the self-regulation of the system functions by adaptation to changing internal and external conditions. In living organisms, this self-regulation is achieved by complex biochemical feedback networks of homeostasis. Trying to copy these networks molecule by molecule is not only troublesome but also inconvenient. Also, the current material platform used to manufacture (plant) robots—plastics, metals, and even soft materials such as elastomers and hydrogels—is different from that of the living organisms, which is biological tissue. However, self-regulation can be adapted very well as a concept in plant robotics. Similar to biochemical feedback, material feedback loops can be built using the models of non-equilibrium materials science. Many literature examples of this type of embodied intelligence [86] in bioinspired self-healing [87] and chemical feedback [88], the use of self-regulation in materials [89, 90] stand as encouraging examples for this endeavor.

The first example of a self-regulating, autonomous plant [85] included hard materials, traditional solar panels, a 3D printed body, and nitinol alloys. Together with the design elements, the alloys allowed thermomechanical feedback in the system that allowed the tracking of the sun (heliotropism) and leaf opening (nyctinasty). The second generation of this plant [36] attained artificial self-regulation through bioinspired transpiration (dehydration/hydration) of hydrogels (figure 2(i)). In both generations, the feedback involved keeping the stem uninterruptedly in a metastable position, which maximizes light on plant leaves. Such a continuous autonomous tracking enables efficient light-harvesting when solar panels are attached to leaves [36, 85], or efficient chemical synthesis when a chemical reaction is coupled to the system [91]. The artificial feedback and thus 'the autonomy level' can be regulated by doping with light-absorbing chemicals or by changing the geometry of the plant robot.

Self-regulation in plant robots and artificial systems through bioinspired material feedback brings in autonomous control and energy efficiency. However, such an autonomy in plant robotics has only a few examples so far. Certainly, the integration of self-regulation by material feedback can be expanded to other lightweight systems of different geometries [36]. As mentioned earlier, improvements in resilience and responsiveness of materials that enable self-regulation are needed. In new systems, all functions displayed by plants and plant parts [28], such as self-cleaning or biochemical signaling, including the most studied photoactivity [92], can serve as the inspiration source. The complex and integrated behavior of the plants, tropic, and nastic movements, energy harvesting, and production of chemicals can all be built into these autonomous artificial systems.

7. Plant-inspired and plant-derived materials

It is clear that functional materials will play a crucial role in developing the next generation of robotics. Likewise, plants repeatedly rely on exploiting particular materials to resolve challenges long known to bear particular features that can serve technology. Among the best known plant-inspired material systems are the snap fastener Velcro [93] and self-cleaning surfaces with superhydrophobicity inspired by Lotus leaves [94]. However, the range of plant-inspired materials is much broader and covers applications and functionality on multiple scales from nanostructures to building architecture [95–100].

Typical features of plant materials that are mimicked are the mechanical properties, the actuation capability, interaction with the environment (especially water and light), cellular geometry, surface topographies, composites, and optical properties. Those must always be seen in relation to the applications purpose in the robotic scenery.

Actuation and autonomous materials have already been mentioned in sections 5 and 6 and are crucial. Another of various examples for a multifunctional passive structure derived from plants are microscale attachment systems based on hooks and spines [32, 101–104] as stated in section 3. However, they are interesting not only as reversible interlocking and attachment solution in a technical scenario. The mechanically extremely stable tips of the micron-sized hooks can also be used to deliver molecules into tissue, attach sensors to leaves, (as shown before in figure 2(d)) and enable climbing of vehicles [32].

Another attachment solution is an example for energy-efficiency obtained through storing elastic energy in composite materials that can be released on demand such as in tendrils. The cucumber tendril uses an asymmetric contraction of a gelatinous fiber ribbon leading to helical coiling that wraps the tendril around a support [105]. The tendril also lignifies which stiffens the tissue and secures the attachment. This was mimicked in silicone rubber mock-ups of the mechanism [105] and in an electrically controlled soft machine capable of coiling around a support triggered by a 30 s current pulse, the only energy input needed for operation [106]. A disadvantage of the latter example is that a sensing functionality has not yet been included allowing the artificial tendril to detect a support and to evaluate if it is suitable for attachment and for further development and function of the system that is being attached. A better such sensing functionality could be provided by the materials and structure itself, the fewer components and computation of sensing data would be required to realize the attachment system.

Such dynamic behavior of materials, as well as the storage of elastic energy in the structure which can be released upon stimulus (compare also Venus flytrap's bistable structures) create a complex, programmable material behavior. Similarly, the autonomously moving materials that absorb and/or release humidity to achieve actuation such as motion of pine cones (see e.g. figure 2(j)) preserved for millions of years [59] shows that such functionality can be extremely robust. Artificial multi-responsive materials such as used in a leaf-inspired microfluidic system (figure 2(k)) can respond to various stimuli such as light, humidity, and temperature and served in a device capable of adaptive photosynthesis [38]. As mentioned above, such properties are totally enabled by the functions and arrangement of composite materials [34, 37, 38, 54, 59, 96, 107].

There are indeed a variety of material solutions in plant tissue from seeds, roots, leaves, flowers, stems, petioles, etc that provide excellent examples to derive concepts like 'embodied energy' [108] and 'physical intelligence' [86, 109] which are key to developing new prospects in robotics to incorporate additional functionality directly in the materials and thereby reducing energy consumption and integral complexity while increasing degrees of freedom and overall sustainability.

This also should include degradability, recyclability, and self-repair of materials for which plants are excellent examples [110]. Biodegradable materials are being increasingly used in robotics and soft robotics exploiting additive manufacturing techniques [111]. Also plant-derived biodegradable materials, in particular cellulose, and wood- or leaf-derived porous materials are gaining increasing interest as a 'regrowing' and sustainable resource for materials in high-tech applications [98, 112]. An example of a programmable deformation due to a patterned stiffness variation realized with 3D-printed cellulose is given in figure 2(l) [39]. Thus, in addition to mimicking plants, significant progress can be made in learning how to advance the library of materials that can be derived from plants, how to process them and use them in new, high-tech applications. This can reduce or replace the use of completely artificial materials by sustainable regrowing materials.

Features like the targeted exchangeability (seasonal exchange of leaves), the biodegradability, recycling (gaining new materials from degradation products of old structures like leaves), and especially the synthesis of new materials through absorption from the environment, based just on chemicals CO_2, ions, and water provide a dimension that is both extremely inspiring and yet still challenging as a strategy for obtaining artificial materials.

8. Living plant-hybrid systems

A special perspective offers the possibility of directly exploiting living plants as components of hybrid devices. Instead of using dead plant tissue or mimicking plant features in artificial matter, living plant-hybrid systems make use of the living organisms physiology, the water content, the turgor pressure, biochemical reactions, and so on. Indeed, it was shown that living plants can be directly used as energy harvesters, sensors, and robot parts. In doing so, this plays an important role to adapt and combine artificial components with the plant in a way that the plant is not harmed in their intrinsic processes and their own development but at the same time it is exploited for a high-tech purpose. Especially the advances in the understanding of material properties, biochemical mechanisms, and physical processes in artificial and biological matter have accelerated the potential that plants can be used for energy conversion [113–118] and environmental sensing (e.g. figure 2(m)) [40, 119–125] by interfacing and modifying the plants with engineered materials and electronics [118, 126–128].

Examples include light-emitting plants [129], plant-hybrid sensing platforms [40, 119–125], plant-internal electronic circuits [130, 131] and plant-hybrid robotics (figure 2(n)) [41], as well as living plant-driven energy harvesting [113–115] using wind [117, 132], rain drops [116], the root/soil microbiome [133–136], components of plant sap [137–139], tissue temperature gradients [140], and potential differences between soil and plants [141] endow great prospects for connecting plants to artificial technology.

Recently, it was shown that plants can be used as multisource energy harvesters. By introducing a coating on plant leaves, the hybrid devices can convert mechanical motion of leaves in the wind and radiofrequency (RF) radiation into electricity that can power wireless sensors (figure 2(o)) [42]. To achieve this, the intrinsic plant structure has been exploited as conductor and leaves have been modified by a thin, harmless, coating not affecting growth and plant development over a year's time. The plant was rendered as a triboelectric generator and the ion-conductive tissue functions additionally as an antenna to receive RF radiation for energy harvesting and powering wireless environmental sensors [42]. A common and strong motive for developing plant-hybrid technologies using living plants is the benefit that the intrinsic plant functionality keeps working providing the added value, CO_2 fixation, O_2 production, self-repair, and many more extremely difficult functions to realize in completely artificial systems are retained in the plant-hybrids. A clear challenge thereby is, that when artificial components are combined with the biological organisms, the artificial components and the organism need to remain functional (especially outdoor in a highly unstructured and rarely predictable environment). Moreover, they should not affect the plant's survival. Thus, artificial components that enable plant-hybrid devices should be specifically designed to fulfil these requirements. If challenges like maintaining the plant healthy and reusable during operation can be tackled, derivation of sustainable, energy-efficient, and autonomous devices, e.g. for environmental monitoring, agriculture, climate change surveillance, ecosystem investigations, can be attained.

9. Conclusions and outlook

Plant-inspired robotics is a still new, yet growing field of research. It has now started to collect important contributions across various communities and disciplines, including ecology, biology, mathematics, engineering, and materials science. Here, we only mention a few of many fascinating technological developments that have been achieved in the field in the last years and we focus on future perspectives and challenges ahead. The strengthening of collaborations across multi-disciplinary domains is clearly of fundamental importance to address the many open questions from the biological model with an engineering perspective. Different from those of animaloid, humanoid and other technologies, 'plantoids' do not have established performance benchmarks. Communities in this field should put more effort in the future to identify applicability criteria to push the technological evolution. The inherently fluidic nature of plant structures is a strategy little-exploited in robotics to date. It is certain that progress in plant-inspired robot structures will coincide with advances in materials research and engineering. In addition, gaining biology-like features including, on-demand, responsiveness, degradability, autonomy, and self-repair could be viable tools to develop artificial systems that better mimic nature. This is specially the case in combining materials with different physical properties and functionalities in one body including features like growth. This might include tissue engineering and synthetic biology as complementary disciplines to enable new strategies for growth, morphing and functionalization in man-made living machines.

Moreover, energy consumption and autonomy require integrating energy harvesting, storage, and distribution and responsive materials in one system. Among features that may be realized are sensors and actuator systems that grow with the artificial system. The different aspects of currently-abstract' concepts, e.g. artificial photosynthesis, may add new functions to the devices. On the other hand, following biohybrid approaches using living plants as parts of devices like energy harvesters and sensors requires expertise on how artificial technology can be merged and integrated to replace components with plant-derived living matter. To achieve plant-hybrid solutions, the key aspects that will need to be addressed are how to best adapt artificial technology to the unstructured and dynamically changing organisms that maintain both the device and the plant functionality, during operation. This requires searching, identifying, and rethinking many traditional design and engineering approaches for which, in turn, plant-inspired approaches could provide solutions.

In conclusion, the results achieved in the last ten years in plant-inspired and plant-hybrid machines have clearly shown the great potential as a source of new technologies—some of which with immediate impact, and others with impact in longer terms on society. Clearly, plants are great role models for achieving the highest levels of environmental sustainability, and energy efficiency. This fact has already reached the attention of scientists, engineers, the society, and the funding agencies. Yet, we are still in the beginning of a growing field—with a great potential and far from saturation—which promises unconventional approaches for the above-mentioned features. These approaches will surely require collaborations across many disciplines and sectors.

Data availability statement

No new data were created or analyzed in this study.

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