Cyborg Botany: Exploring In-Planta Cybernetic Systems for Interaction

Harpreet Sareen
Parsons School of Design`
New York NY 10011
sareen@newschool.edu

Pattie Maes
MIT Media Lab
Cambridge MA 02139
pattie@media.mit.edu

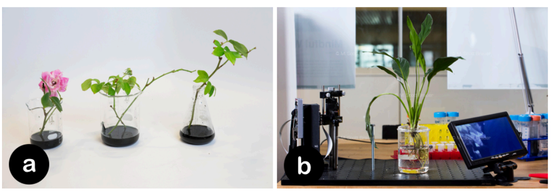

Fig 1: a) Plants with new conductive channels or wires grown inside them, b) A Lead Sensing Plant with chemical sensors in the leaf of the plant

ABSTRACT

Our traditional interaction possibilities have centered around our electronic devices. In recent years, the progress in electronics and material science has enabled us go beyond chip layer and work at the substrate level. This has helped us rethink form, sources of power, hosts and in turn new interaction possibilities. However, the design of such devices has mostly been ground up and fully synthetic. In this paper, we discuss the analogy between artificial functions and natural capabilities in plants. Through two case studies, we demonstrate bridging unique natural operations of plants with the digital world. Each desired synthetic function is grown, injected carefully or placed in conjunction with a plant's natural functions. Our goal is to make use of sensing and expressive abilities of nature for our interaction devices. Merging synthetic circuitry with plant's own physiology could pave a way to make these lifeforms responsive to our interactions and their ubiquitous sustainable deployment.

CHI'19 Extended Abstracts, May 4-9, 2019, Glasgow, Scotland, UK.

ACM ISBN 978-1-4503-5971-9/19/05.
DOI: https://doi.org/10.1145/3290607.3313091

KEYWORDS
Augmented Plants; Sensors; Interaction Design

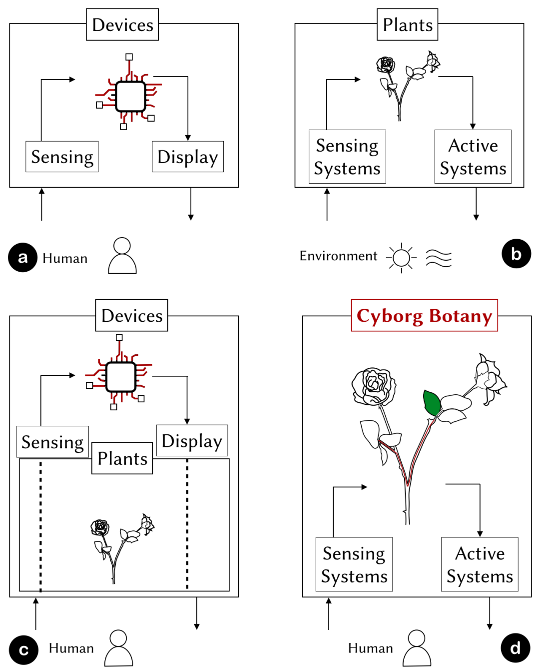

Fig 2: a) shows components involved in artificial interactive devices, b) shows plant systems responding to environment. Notice the analogy between artificial devices and plants systems in a) and b) together. c) represents the current approach of electronics external to the plants, d) merger of systems with plant's own capabilities to perform interaction functions through plants

INTRODUCTION

The nature has myriad beautiful organisms, with many of them carrying unique sensing and expression abilities. They can sense the environment, other living entities and regenerate, actuate or grow in response. Our interaction mechanisms and communication channels with organisms in nature are subtle, unlike our interaction with digital devices. Take for example, plants, that convey silently about lack of water [1], nutrient deficiencies [2] or time of day [3,4]. Lately, for our interaction needs through devices such as sensors and displays, our approach has been to build entirely new mechanisms. However, to enable such interactions, we can potentially tap into the capacities already built into the nature.

In this paper, we propose a new convergent framework of designing through nature. We focus on plants and showcase two case studies of deep technological integration with them. The physiological working of a plant enables artificial functions installed inside it, without harming the plant itself. Through example applications, we demonstrate such hybrid species, which could potentially carve a new method to design interfaces in the nature. Our contributions are:

- Application space of conductive wires grown inside a plant, with an example of plants as antennas/motion sensors
- Nanosensors inside plant leaves that provide visible optical/digital readout of surroundings

RELATED WORK

Plants generate electrical gradients or potentials in response to the changes in light, gravity, luminous intensity and many other factors. The first recording of action potentials in plants was observed by John Burdon-Sanderson in the Venus Flytraps [5]. Sanderson measured the voltage difference between adaxial and abaxial surfaces of a Dionea leaf while he stimulated the leaf hairs mechanically. Subsequent experiments were done by Bose on the Mimosa Pudica plant, wherein he linked the plant movement to the electrical signals [6].

Artists and Designers

Artists and designers have viewed the plant signals as a form of communication with the outside world. Plantron [7] exposes the hidden plant signals through an audio interface for humans to understand how they affect the environment. Florence [8] is a conversational interface with the plants. It uses natural language processing to convert human language into light modulation for the plant and subsequently translating their electrochemical signals.

In HCI

To achieve pleasing/unobtrusive designs, researchers have previously attempted to use plants as information displays. Infotropism [9] is a living plant display that informs individuals about relative contributions to recyclables and trash. Mossxels [10] uses blocks of moss called Racomitrium canescens and is able to do slight a change in appearance by controlling humidity on patches.

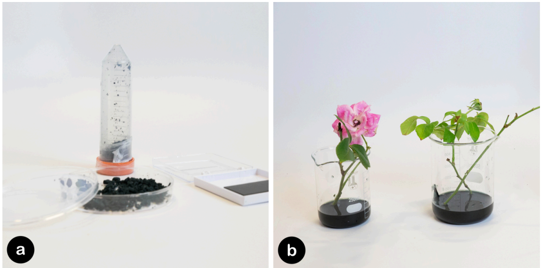

Fig 3. PEDOT-S in a petridish before the experiment b) Fresh cut plant stems were kept in 1:1 solution of PEDOT-S with water for 48 hours. Followed by uptake, the solution polymerizes to a hydrogel wire inside the plant xylem

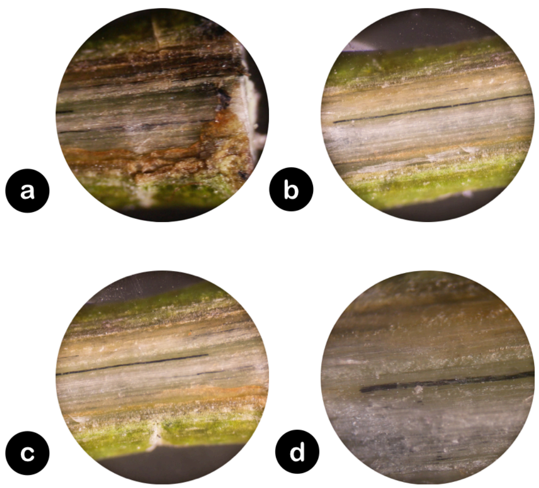

Fig 4 a) Peeled off sections from the stem showing xylem, b) & c) Sections of the same stem 7cm apart (4x mag), d) shows the wire at a higher magnification (10x). uScope: Omega EXC-500

Botanicus Interacticus [11] is technology to use plants as input interfaces. A single electrode is placed in the soil with a frequency sweep program that detects when/where an individual is touching a plant. Other instances of attaching external electronic devices to plants are EmotiPlant [12], I/O Plant [13] where researchers put arbitrary sensors on plants for interaction with humans. Examples of their system include light-emitting diodes (LEDs) and gas sensors attached on a plant to inform users about plant's own health or quality of environment around it.

The common theme running through the above works is to deploy external electronics (Fig 2c) to interface with the plants for inputs or outputs. In our case studies (Fig 2d), we focus on interfacing with capabilities inside the plants themselves to establish bidirectional input-output. Such bionic means of integration could lead to large-scale deployment schemes, novel interfaces and/or contextually pleasing outputs.

Through Cyborg Botany, we propose a merger of bionic materials with the physiology of plants for interaction design. Such a merger of electronics and plants leads to real-time sensing, actuation mechanisms and more. The real-time aspect of such techniques are key to new interaction design possibilities with the nature.

PLANT ELECTRONIC INTERFACES

Planta Digitalis

In this study, we grew conductive wires inside plants and use the plants as antennas and motion sensors. A large number of land plants have tissues for conducting water (lignified tissue, xylem [14] and products of photosynthesis (non-lignified tissue, phloem [15]) throughout the plant. These vascular channels draw solutes from the soil through a network of vessels or tracheids [16]. Such distribution is analogous to channels, connections and outputs in electronic circuits.

Process

We use a Rose (*Rosa Floribunda*) plant (Fig 2) for this experiment owing to its large vascular channel (>50 µm). Based on the material identification with plant channel size [17,18], we used PEDOT (source: Sigma-Aldrich) as the organic conductive polymer. PEDOT [19] is a synthetic organic polymer commonly used in antistatic packaging, solar cells and more. As per the recommended protocol, a water-soluble variant of PEDOT [20] was added in which stem cuttings of Rose were kept for 48 hours. The barks of two specimens were peeled and observed under a microscope for wires up to 30um thick and an average 6-8 cm (approx.) long.

Hardware

Stem cuttings from the wire grown specimens were taken and peeled at two different locations. The longest direct growth was 8.2 cm (µscope: Omega EXC-500) with conductivity of 0.18 S/cm. A shielded platinum electrode was carefully inserted to make contact with the wire at one end and the other end connected to a 3ft long Subminiature Version A (SMA) wire. The SMA wire was connected to a matched Device Under Test (DUT) port of a Vector Network Analyzer (Fig 5 a, c).

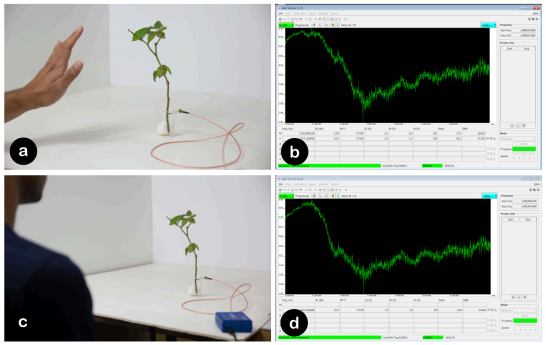

Fig 5. Data being logged from miniVNA/J application to a text file for classification later on openFrameworks

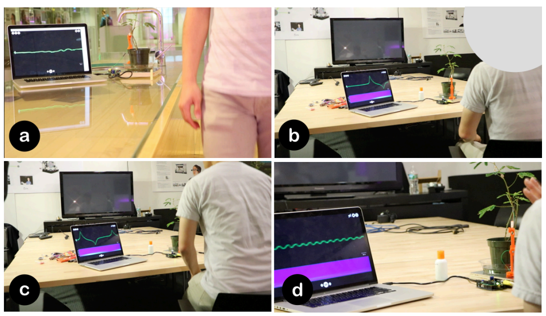

Fig 6. Signal data feeding in an oF application. Patterns of certain activities are distinct making classification possible

Proper shielding on the wires was ensured (with prior run showing no reflectance peaks in the measurement range) and care was taken to reduce external interference sources. The analyzer (miniVNA Tiny, Sampling range: 1MHz to 3GHz) was previously calibrated with DET/DUT open, DUT short and DUT under load. The peak frequency of reflectance was observed with a single scan at 1570MHz (or 1.57GHz). The scanning range was subsequently reduced to 1.2-1.8 GHz with free run enabled and at the highest (sampling) speed on the VNA/J analyzer application. The data was continuously logged in a text file feeding input to an openFrameworks application for custom analysis. A preliminary nearest neighbor algorithm measures the current range values and chooses the closest match of previously stored values for hand proximity, sitting/standing, and walking activities around the connected plant.

With this setup, continuous change in RL (dB) values is observed at a fixed frequency range as the user is in proximity, waves, sits or stands around the plants. These are classified using the above-mentioned methods and logged as results. The in-vivo wires along with the frequency sweep help engineer antenna-like electromagnetic properties in plants (Fig 6). The interference patterns or coupling with EM waves can thus be used for broader applications in the future.

Application Space

Plants with new in-vivo conductive channel have wider interaction possibilities than motion or activity tracking. For e.g: Growing wires in plants with spiral morphology and transmitting audio signal through them can render them audible. House plants can be actuated through in vivo channels to communicate directly about their health or external environment. In essence, the wires can be used to receive input from plants or to actuate them for various functions.

‘IN-PLANTA’ NANOSENSORS

An auxiliary sensing system can be powered by placing it in conjunction with a plant’s natural system. Such new capabilities as seen previously do not have to be external but can now reside inside the plant organelles [22]. In this experiment, we show heavy metal (Lead, Pb2+) sensing capability inside a houseplant. The ‘in-vivo’ rapid detection is interfaced with the digital world, with the vision of a greater detection palette and bidirectional relay channel with the plants.

The precedents follow from agricultural biotechnology and nanomaterials to make plants resistant to diseases, enhance their nutrient absorption and more. Several nanomaterials and their effects have been studied on plants [23]. Carbon-based material such as Carbon Nanotubes (CNTs) have been shown to penetrate the seeds [25] and plant cells [26]. We prepare chemical sensors that can reside inside the leaf of a plant and stay within its intercellular space. For our sensors, we use the DNA cleavage approach by Yao et al. [24] but modify it for in-vivo detection in plants. We prepare ‘8-17 DNAZyme’ turn-off assay where 5'-end of strand is labelled with a quencher and 3'-end with a flourophore. As per this protocol [19], the dsDNA (double stranded DNA) in presence of Pb^{2+} is cleaved to ssDNA (single stranded DNA) that binds more strongly to SWNT walls, thus fluorescence is in turn proportional to the Lead(II) concentration.

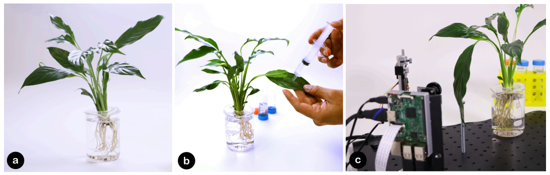

Fig 7. a) Spathuphyllum plant in DI Water culture, b) Leaf infusion of oligo-functionalized CNTs through the abaxial side of the leaf. c) Laser diode to excite the dsDNA nanosensors inside the leaf. While flourescence and subsequent quenching is observable in the visible domain, RPi digital detection can bridge plant detection to digital software and aid in long term observation/logging.

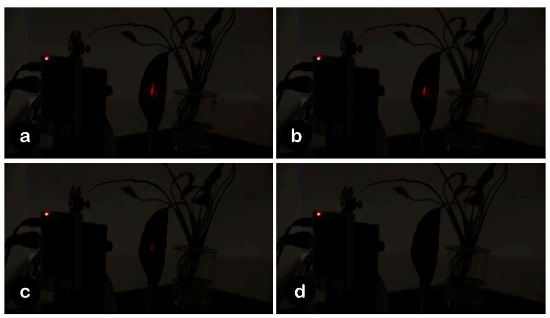

Fig 8. Visible lights turned off in the room before fluorescence readings. CNT sensors produce fluorescence (~640nm) when shone with 550nm laser. After introduction of Lead (Pb2+), quenching of fluorescence is observed in-vivo. Timeline: a=15min (100% intensity), b=30min (80%), c=100min (20%), d=150min (Full quenching)

Process

A Spathiphyllum plant system (8 weeks old, Fig 7a), normally used as a houseplant was chosen for testing the sensors to show the applicability in homes. A needleless syringe (Fig 7b) was used to do infusion of the above CNT chemical sensors [21] through the abaxial side of the leaf. The leaf was cleaned of any remaining assay on the surface. A laser laser diode of 550nm (Renesas NX7538BF-AA, fig 7c) is used to excite the dye labelled sensors inside in the leaf and get the fluorescence output (~640nm). The excitation wavelength (i.e. 550nm) for SWCNT solution was as measured previously with a spectroflourometer. This was chosen for the experiment owing to low absorbance of the plants between 500nm- 600nm wavelengths. 20uL of Pb2+ metal ions were then introduced in the beaker using a micropipette. Following introduction of Pb2+, the red fluorescence previously visible on the leaf was observed to turn-off in ~150mins (Fig 8).

Traditional Pb2+ sensing isn't an easy off-the-shelf electronic sensor work. Sophisticated instrumentation and a number of days are required for such analysis. To interface our plant-based Lead detection with the digital world, we built a non-specialized setup with a Raspberry Pi and a full spectrum camera. A long pass filter of 600nm (ThorLabs FEL600) is placed in front of the camera. A camera program is able to detect presence/absence of fluorescence from the leaf of the plant with information about the heavy metal (Lead, Pb2+). When the blob is visible, the output is interpreted as heavy-metal free. Following introduction of Pb2+, the laser output is quenched inside the plant (Fig. 8).

Application Space

Such an approach can be useful at home interfacing with the activities we usually do at home. Watering a house plant regularly could tell us about the chemical levels in water. Sensors for detecting other elements can also be deployed in industrial or nuclear towns for continuous monitoring.

CONCLUSION

We introduced the concept of Plant Bionics where our interactive functions of the future could be powered and co-exist inside the plants. The electrical and biological systems are analogous on an abstract level and could be bridged in the future. We discussed the design goals of such interfaces and their potential implications in scale, ubiquity and sustainability. We presented two case studies of how such functions could be designed: i) Conductive channels inside plant vasculature that act as motion sensors, and ii) Synthetic sensors in cellular organelles that monitor environment naturally. The result is a series of hybrids with a complex intertwining of technological capabilities placed in association with the plant functions.

REFERENCES

[1] OurHousePlants. https://www.ourhouseplants.com/plants/peacelily. [Online]. "https://www.ourhouseplants.com/imgs-content/peace-lily-3.jpg"

[2] Cakmak, Ismail, and Horst Marschner. "Magnesium deficiency and high light intensity enhance activities of superoxide dismutase, ascorbate peroxidase, and glutathione reductase in bean leaves." *Plant physiology* 98.4 (1992): 1222-1227.

[3] MissouriBotanicalGarden. Maranta leuconeura (Prayer Plant). [Online]. "http://www.missouribotanicalgarden.org/PlantFinder/PlantFinderDetails.aspx?kempercode=b604"

[4] Ulrich, and Winslow R. Briggs Kutschera, "Phototropic solar tracking in sunflower plants: an integrative perspective," *Annals of botany*, vol. 117, no. 1, pp. 1-8, 2015.

[5] Burdon-Sanderson, J. "Venus fly-trap (Dionaea muscipula)." *Nature* 10.105-107 (1874): 127-8.

[6] J. Bose, "Nervous Mechanism of Plants," *Longmans*, 1906.

[7] Dogane, Y. (2011, September 24). Ecological Plantron. Retrieved September 18, 2018, from Samtidskunst: http://www.samtidskunst.dk/simpleinteractions/en/projects/yuji- dogane/

[8] Steiner, H. e. (2017). Project Florence: A Plant to Human Experience. Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems (pp. 1415-1420). Denver: ACM

[9] Holstius, D. (2004). Infotropism: living and robotic plants as interactive displays. In Proceedings of the 5th conference on Designing interactive systems: processes, practices, methods, and techniques (pp. pp. 215-221). ACM.

[10] Kimura, T. (2014). MOSS-xels: slow changing pixels using the shape of racomitrium canescens. In ACM SIGGRAPH 2014 Posters (p. p. 20). ACM.

[11] Botanicus Interacticus: interactive plants technology. In ACM SIGGRAPH 2012 Emerging Technologies (p. p. 4). ACM

[12] Angelini, L. (2016). Multi-sensory EmotiPlant: multimodal interaction with augmented plants. In Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct (pp. pp. 1001-1009). ACM.

[13] Kuribayashi, S., Sakamoto, Y., & Tanaka, H. (2007, April). I/O plant: a tool kit for designing augmented human-plant interactions. In *CHI'07 extended abstracts on Human factors in computing systems* (pp. 2537-2542). ACM.

[14] A. G. Volkov, "Green plants: electrochemical interfaces," *Journal of Electroanalytical Chemistry*, vol. 483(1), pp. 150-156, 2000.

[15] A. G. Volkov, *Plant electrophysiology.*: Springer Berlin, 2012.

[16] Johnsson, Anders, Vijay K. Sharma, and Wolfgang Engelmann. "The telegraph plant: codariocalyx motorius (formerly also Desmodium gyrans)." *Plant Electrophysiology*. Springer, Berlin, Heidelberg, 2012. 85-123.

[17] E., Gabrielsson, R., Gomez, E., Crispin, X., Nilsson, O., Simon, D. T., & Berggren, M. Stavrinidou, "Electronic plants," *Science advances*, vol. 1, no. 10, p. e1501136, 2015.

[18] Stavrinidou, E. et al. (2017). In vivo polymerization and manufacturing of wires and supercapacitors in plants. *Proceedings of the National Academy of Sciences*, 201616456.

[19] Y. (2009) Wang, "Research progress on a novel conductive polymer–poly (3, 4-ethylenedioxythiophene)(PEDOT)," *In Journal of Physics: Conference Series*, vol. Vol. 152, no. No. 1, p. p. 012023.

[20] H., Jo, T., & Okuzaki, H. Yan, "Highly conductive and transparent poly (3, 4-ethylenedioxythiophene)/poly (4-styrenesulfonate)(PEDOT/PSS) thin films," *Polymer journal*, vol. 41, no. 12, pp. 1028-1029, (2009).

[21] M., Greden, L., & Arbona, J. Joaqim. Human Ecology Design, MIT. [Online]. "http://www. archinode. com/bienal. html"

[22] X., Zhou, G., Liu, Y., & Wang, Y. (2010, December). Jiang, "Wireless sensor networks for forest environmental monitoring," in *2nd International Conference on Information Science and Engineering (ICISE)*, 2010, pp. (pp. 2514-2517).

[23] X., Wang et al. "Research progress on electrical signals in higher plants," in Progress in Natural Science, vol. 19(5), 2009

[24] N. Wiener, *Cybernetics or Control and Communication in the Animal and the Machine.*: MIT Press, 1961, vol. Vol. 25

[25] A. Husen, "Carbon and fullerene nanomaterials in plant system. ," *Journal of nanobiotechnology*, vol. 12, no. 1, 2014

[26] Q. Liu, "Carbon nanotubes as molecular transporters for walled plant cells. ," *Nano letters*, vol. 9, no. 3, pp. 1007, 2009