# Cyborg Botany: Augmented Plants as Sensors, Displays and Actuators

by

Harpreet Sareen

Submitted to the Program in Media Arts and Sciences,
School of Architecture and Planning,
in partial fulfillment of the requirements for the degree of

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## Abstract

Plants are photosynthetic eukaryotes with a billion years of evolutionary history. While primarily sessile, they have developed distinctive abilities to adapt to the environment. They are self-powered, self-fabricating, self-regenerating and active signal networks. They carry highly advanced systems to sense and respond to the environment. We strive for such sensing and responses in our electronics; self-growing or self repairing abilities in our architecture; and being sustainable at scale in general. The industrial and technological thought process has mostly been devising artificial means or replicating natural systems synthetically. However, I propose a convergent view of technological evolution with our ecology where techno-plant hybrids are created. The approach is to formulate symbiotic associations and to place the technology in conjunction with the plant function(s). In this thesis, I go from the outside to inside the plants in conceiving such synergetic processes and present case studies of their implementation and analysis. I begin with a robot-plant hybrid where the robotic device adds mobility and is triggered with the plant's own signals. Next, lead (II) detection nanosensors are presented which reside inside the leaf of a plant and continuously sample through plant hydraulics. This is followed with a design study for plants with new conductive channels grown inside them and their subsequent use as inconspicuous motion sensors. I conclude with a symbiotic robot that lives on a sunflower plant and automatically trains or directs its growth with on-board lighting. The end result is an augmented-plant society where technology adds non-native functions or redirects the natural processes.

Thesis Supervisor: Pattie Maes
Title: Professor of Media Arts and Sciences

*To Grandpa*

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# 1. Introduction

*"To exist is to change, to change is to mature, to mature is to go on creating oneself endlessly."*
*Henri Bergson, Creative Evolution*

**Technology and the "Umwelt"**

French philosopher Simondon describes technological objects as part of the human nature evolving through 'concretization' (Schmidgen, 2005). His notions emphasize the dynamic between objects and '*umwelten*' (environment) in a continuous dialogue to adapt. Such machine philosophy sees technological and biological beings together as also seen in the cybernetic theories (Wiener, 1961). According to Wiener, a cybernetic entity is an organism-machine hybrid where 'machine parts become replacements, integrated or supplemented' to an organism's body image (Featherstone, 1996). While we have seen such integration with humans, technological convergence with our ecology in this manner hasn't happened yet. A successful union can render our environment stronger and accessible for functions we desire in our synthetic world. In this thesis, I propose

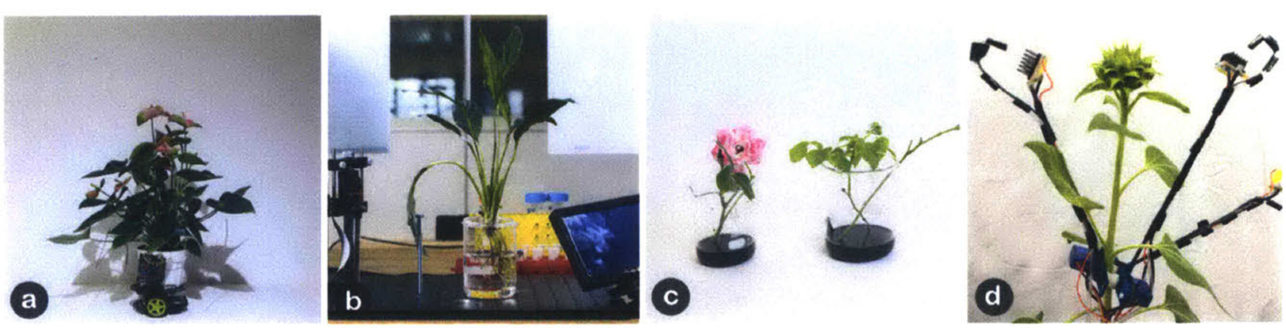


Figure 1.1 a) Elowan - A Robot Plant Hybrid driven with plant's own signals, b) A Lead Sensing Plant with chemical sensors in the leaf of the plant, c) Plants with new conductive channels or wires grown inside, d) A sunflower-climbing robot hybrid that

such tech mutations with the plant life. The result is a series of hybrids with a complex intertwining of technological capabilities placed in symbiotic association with the plant functions.

## 1. 1 Thesis Aims

This thesis builds on the overarching vision of an augmented nature, aspiring for convergence in what we do in our technological world and the inimitable aspects occurring naturally. Making nature a part of our design process and ushering in a new bio-interaction design will be a key to ubiquitous sustainable interactions. This thesis hopefully inspires designers to 'conduct their practice with and for elements and species in nature'.

Through a few case studies in the chapters that follow, I demonstrate how plants can be the ideal substrates for some of our technological solutions. A lot of thought went into observing the functions in *flora* and I hope the reader observes the pattern of synergies that emerged. The end result is new techno-plant societies, where bio-hybrid systems can be viewed as singular robotic, electronic or architectural artifacts.

These augmented species when in a single greenhouse were evocative to me of an 'alternative ecology', something that I call as a 'Cyborg Garden'. I am hopeful that this is just the beginning and a complete high bandwidth and bidirectional bridge between the digital and plant worlds will endow us with capabilities we could previously only imagine.

## 1. 2 Thesis Overview

This thesis posits the symbiosis of plants with our technological world. In an effort to bring new properties to the synthetic world from our natural realm and vice versa, a series of case studies that follow attempt to provide an answer. Such hybrids may offer the best of both worlds for designers, engineers and architects. With plant biology as the common denominator, I discuss intersection in interaction design, electronics and architecture. Each chapter (4 - 8) is a synthetic capability placed in conjunction with a plant function. For a reader pressed with time, the following outline summarises each chapter and hopefully encourages to delve further.

**Chapter 2** describes the motivation behind this body of work and why flora can and should be integrated with our technology.

**Chapter 3** presents related work by artists, biologists, engineers and designers and serves as an inspiration on how plants have figured in many applications they would not be imagined for.

**Chapter 4** is an experiment that connects natural movement/expression mechanism in plants with the digital world. A new bio-actuation technique is presented wherein physical leaves of a plant are actuated while an individual clicks on their position in a software application.

**Chapter 5** is an artistic exploration on what augmented plants would mean and concludes with a robot driven towards light through a plant's own signals.

**Chapter 6** is a design study on plants with conductive wires grown inside, used for motion/activity tracking in the environment. A design space is also charted for such plants with in-vivo conductive channels.

**Chapter 7** presents CNT-Based Nanosensors that are injected in leaf of a plant. The sensors produce optical readout when in contact with lead (II) in water that is sampled through plant transpiration/uptake mechanism.

**Chapter 8** is a study on directing the growth of a plants robotically. A robot with on board lighting climbs on a plant while directing and adjusting its position. Outputs of 12 weeks of growth experiments in total are presented with the final shapes of plants.

**Chapter 9** concludes limitations of some of the techniques and a discussion on the future of augmented plants.

## 1. 3 Thesis Contributions

My intention through this thesis was to wear multiple hats and to tie the contributions in both design and engineering worlds. I summarize my contributions as follows:

- A bio-actuation interface where individual leaves of a plant can be actuated through a digital application
- A plant-robot hybrid where plant's own electrochemical signals trigger robot movement
- A design study of plants as motion/activity sensors with conductive wires grown inside them and a design space for such plants with different morphologies
- In-vivo CNT-Based detection turn-off fluorescence sensors sampling Lead (II) through plant uptake and visible readout
- A mechanism of directing plant growth with robots that live on plants and training for different shapes through onboard lighting

# 2. Motivation

*"Plants are nature's alchemists, expert at transforming water, soil and sunlight into an array of precious substances, many of them beyond the ability of human beings to conceive, much less manufacture."*
*– Michael Pollan, Botany of Desire*

A billion years ago, a major evolutionary episode led to the first organisms that were able to produce energy for themselves. These photosynthetic autotrophs – *the algae* – were the first self-powered systems deriving energy from inorganic molecules, later evolving to land plants. Fast forward half a billion years and plants developed fundamental abilities to self-fabricate, self-regenerate and on-board generation of power. They also carry highly advanced systems to sense and respond to the environment.

The humans first domesticated the plants for farming, increasing production over the years using the plough, machinery and agrochemicals. The technological practices to control biological phenomena and nature of our own bodies extended to animals and plants. We opt for bionics on our bodies and cybernetic extensions to become optimized and efficient. It is only natural to think of a cross between machines and plants – an '**augmented ecology**' where plants could become more robust, expressive and multi-functional.

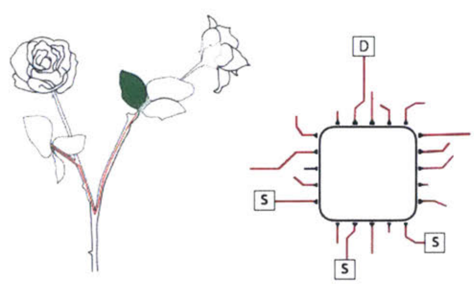

Figure 2.1 Similarity between a Plant and Electronics architecture [S: Sensors, D: Displays]

I will try to explain how we are already doing this and the need of a co-evolutionary design approach, instead of a divergent path from nature. The parallels between the plant architecture and our electronics make this even more desirable. Plants are nutrient autosamplers, natural signal networks (with electrical and chemical signaling) exhibiting mechano/photo-sensory responses in nature.

Figure 2.2 Electrical signals in plants a) Mimosa Pudica plant connected with silver electrodes to a circuit, b) A stick hitting secondary stem of the Mimosa plant, c) The signal output showing an action potential inside the plant [Refer Appendix B Sec. 2.1 for circuit]

Figure 2.3 Sensory responses of plants to environmental stimuli a) Positive phototropism: Movement towards light, b) Gravitropism: Shoot growth opposite to gravity, c) Thigmotropism: Growth towards support structures

Consider, for an instance, TidMarsh wetlands where sensor networks have been deployed to monitor environmental data. Plants, however, already produce electrical responses to various changes in the environment (more in Chapter 5). An inbuilt digital connection for such signaling or a direct readout can potentially turn plants into ideal platforms for sensor deployment.

Figure 2.4 a) Sensor node hardware used in Tidmarsh wetlands (Credit: Responsive Environments, MIT Media Lab, b) UDSA Smart Forests Program (Credit: Fernow Experimental Forest, WV, USA), c) Monitoring microclimate in forests (Credits: Fraunhofer Institute for Microelectronic Circuits and Systems)

Aside from monitoring devices, our interaction and display devices are also becoming pervasive. A synthetic circuitry with new capabilities merged with plant's own could help realize bionic functions in these lifeforms, making them aware and responsive to our interaction. For instance, the natural expressivity or augmented fabric of the plants could be used as displays, circuits could be self-powered or self-regenerating and plants could sample ground elements for electronic circuits inside them.

This forms the motivation behind this work – the development of a transspecies – '**half plant, half machine**' or '**cybernetic plants**' – where augmented plants are more robust systems and able to serve additional functions for us. The success of such concepts could mean scalable future solutions for sensing, interfaces and architecture while being convergent with nature.

In this thesis, I investigate some of these symbiotic relationships between capabilities of plants and current artificial technologies to envision new electronic-plant or robot-plant societies.

I begin by looking at the existing concepts and state of the art in the next chapter.

# 3. Related Work

*"Late twentieth century machines have made thoroughly ambiguous the difference between natural and artificial ... and many other distinctions that apply to organisms and machines" – Donna Haraway, A Cyborg Manifesto*

Plant cells possess the ability to become excited (bioelectrochemical excitation) under the influence of external factors. These are not only stress responses but normal biological functions such as photosynthetic processes. The conduction of these excitation signals in tissues and organs leads to synchronization of internal functions with the environmental responses. (Volkov, 2012).

This thesis relies on the understanding of the biological makeup and response methods built in the plants. The vision of cyborg or augmented plants could mean harnessing these inbuilt processes or introducing new symbiotic functions. The ideas in this manuscripts are at the collision of one or more of these fields: plant sciences, robotics, nanobiotechnology, architecture and human computer interaction. As such, we'll look at the state of the art in these areas in our context.

## 3.1 Plant Electrophysiology

The excitability and conduction of electrical signals is a fundamental property of living organisms. Plants generate electrical gradients or potentials in response to the changes in light, gravity, luminous intensity, osmotic pressure, wounding, chemical compounds and water potential. These potentials are described as action or variation potential depending on normal or stress response in the environment. The first recording of action potentials in plants was observed by Sir John Burdon-Sanderson in the Venus Flytraps (*Dionea Muscipula*, 1874). 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 (in 1906), wherein he linked the plant movement to the electrical signals (Bose, 2011).

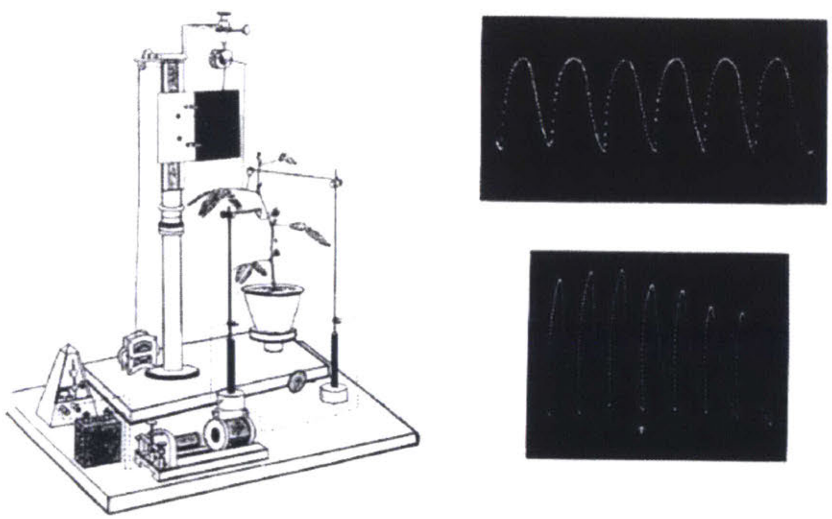

Figure 3.1 Bose experiment on turgor decrease/cell contraction followed by stimulation and leaf-dipping in the Mimosa Pudica. (Experiment dated: 1906, Photo credit: IISC, Bangalore India)

The research on electrical signaling in plants continued through the century on various plants, their organs and factors involved resulting in a decade old journal (Plant Signaling & Behavior). Several projects try to employ the electrical signaling behavior. Trees as Sensors (Fletcher), Jeremijinko's OneTree (Natali) and Pleased (WLAB) view the plants as information processing organisms and their use as low-cost distributed sensors in the environment. Nanoelectronic circuits (Himes, 2010) use live trees and the electrical potentials inside them as a source of their power supply.

Figure 3.2 Plantron by Yuji Dogane is an audio interface to understand the plant's interaction with the environment

Artists and designers have viewed the plant signals as a form of communication with the outside world. Plantron (Dogane, 2011) exposes the hidden plant signals through an audio interface for humans to understand how they affect the environment. Florence (Steiner, 2017) 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.

## 3.2 Plants and Robots

The ruminations on co-existing flora and robot societies have only been a few, predominantly in the spheres of art. Telegarden (Goldberg, 1995) was a community garden that could be tended to by an industrial robotic arm with controls over the internet. The plot encircling the robotic arm, was cultivated by thousands of people over the years before being finally decommissioned.


Figure 3.3 a) Telegarden allows users to view and interact with a remote garden filled with living plants, b) Soybots are robots outfitted with planter boxes and sensors to track light, c) Phytowalkers are robots built with materials from nature such as plant branches, d) Parasitic explores tension between nature and technology with a robot that inscribes on trees. Credits Respective Artists

In line with the concept of gardens and machines, Soybots (McMullen, 2016) and Floraborgs (Demaray, 2014) are sensor-equipped robots outfitted with planters. The light sensors on the robots guide the movement in search of optimal lighting conditions for the plants. On the other hand, in Elowan (Plant hybrid robot, Chapter 5), I interface the signals of a plant directly with a robot. In doing this, the machine is in a dialogue with the living organism than being close but separate entities. The composition of this single being leads to autonomy of the plant while situating technology in coherence with the plant's own capabilities and natural responses.

Other projects such as Phytowalkers (Yamaoka, 2016) look at robots where natural materials such as branches of a tree are used as locomotion elements alongwith an artificial drive mechanism. Parasitic (Krenz, 2016) investigates the tension between nature and technology through a milling machine robot that carves text on a tree.

## 3.3 Inside the Plants

Humans have always tried to use the nature for their survival. Biotechnology taught us how to look inside our own bodies and was then used to look and modify the plant cells for better produce.

### 3.3.1 Synthetic Biology circuits

As new tools to program biology become more available, researchers are starting to look at coding new functions inside living organisms, including plant cells. Of a few precedents, Plant Sentinels (Antunes, 2011) are computer designed explosive (TNT) detector proteins (programmed genetic circuits) that are introduced into the plants. These detectors produce a programmed de-greening response in the leaf when it comes in contact with an analyte. In addition, the researchers have also shown a general-purpose strategy to design biosensors (Feng, 2015) in the plant cells.

The expression times in synthetic biology however are very high, often in the order of days. In contrast, the electronic sensors and their outputs on the temporal scale are close and real-time. To establish a biology to digital bridge as envisioned, a more hybrid approach has to be espoused. My work in Chapter 7 envisions a bioelectronics approach for the plants and is situated between the real-time response of electronics and high expression times of synthetic biology. Besides, this approach allows population control of sensor-plants in contrast to the synthetic biology approach.

I believe synthetic biology paves a way for inheritable detection, readout and straightforward deployment channels. Future strategies of digitally controlled activation/deactivation and real-time readout when realized will be a promising way to get the best of both worlds.

### 3.3.2 Nanobiotechnology

Following plant biotechnology, nanotechnology has also made its way in plant sciences owing to its agronomic applications (Torney, 2007; Tiju, 2006). The applications include in-vivo analytical techniques, target-specific delivery of biomolecules and controlled release of agrochemicals. Researchers have investigated carbon-based nanomaterials (Husen A. , 2014) to silver, silica (Masarovičová, 2013) and more.

Single-walled Carbon Nanotubes (SWCNTs: diameter ~1nm, Tube length up to a 100 nm) have been shown to cross plant cell barriers (Serag, 2013). These can pierce the cell wall to support water intake, in turn affecting germination and overall growth of plants (Khodakovskaya, 2009). As a result, CNTs can be used as vectors to deliver molecules to plant cells. Liu at al.

demonstrated this usage of CNTs as molecular transporters (Liu, 2009) of FITC (*a fluorescein labeller*) in the walled plant cells.

On the other hand, carbon nanotubes have had considerable success as a platform for next generations sensors (Sinha, 2006). The researchers combined the CNT sensors with their internalization properties to show the first plants with higher photosynthetic electron activity (Giraldo, 2014) and later detection of nitroaromatic compounds (Wong, 2017).

In my work, I propose new sensing plants with capabilities to detect heavy metals (*Lead/Pb2+ specifically*) in water. This approach relies on functionalized CNTs with oligonucleotides that have affinity to $Pb^{2+}$ ions as explained in Chapter 7. In contrast to the previous work, I bring the detection readout to visible range relying on negligible absorption of plants in the green spectrum (500-570nm). Such visible readout could pave a way to straightforward electronics-free detection schemes.

In addition, I show preliminary investigation on using plants as antennas and motion sensors with wires grown inside them. This speculative enquiry builds of from high school food dye experiments where benign molecules express color at the top of a flower. We replace the food dyes with organic conductive materials tested on plants by researchers (Stavrinidou, 2015) followed by a short discussion on applications.

## 3.4 Architectures and Displays

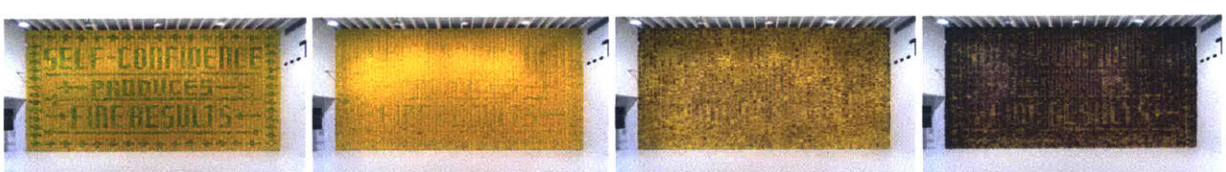


Figure 3.4 Banana Wall by Sagmeister. Type/Message disappearing with time [Credits: Sagmeisterwalsh]

Figure 3.5 Chlorophyll Apparitions by Ackroyd and Harvey. Pictures produced through photographic photosynthesis with strains of stay-green grass. Credits: Artists

Artists have used living organisms such as plants as their media, at times crossing the cultural divide to science. A dazzling example is the work Chlorophyll Apparitions by the pair Ackroyd and Harvey (Ackroyd, 2001). The duo discovered photographic photosynthesis - a process to selectively expose regions of grass to light achieving shades from yellow to green for living pictures. Their later work with scientists resulted in more enduring pictures with strains of stay-green grass. Recently, Sagmeister used plant produce such as bananas for an ephemeral message wall (Sagmeister, 2015).

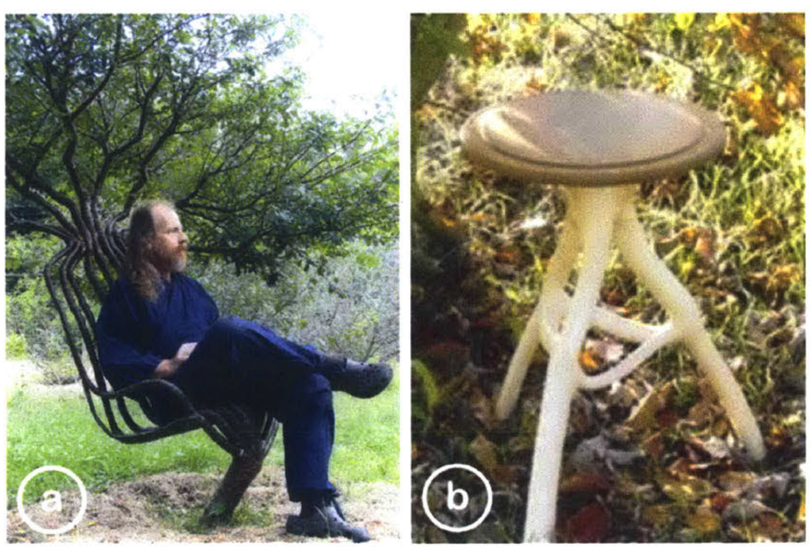


Figure 3.6 a) Living garden chair (Peter Cook), b) Grown furniture (Chris Cattle). Source: Wiki – Tree shaping

In an alternative custom, living trees are used as a medium to create structures and art. The practice commonly referred to as Arborsculpture (Reames, 1995), involves manual tree shaping through techniques such as grafting, framing and pruning. The trained tree outputs can range from waterway bridges (self-growing, self-repairing) to furniture and and other architectural forms.

My work in Chapter 8 describes preliminary methods for automation of tree shaping with symbiotic robots that live on the plants. These robots direct the growth of a plant through various means while powering its growth simultaneously.

## 3.5 In Human Computer Interaction (HCI)

The HCI field traditionally investigates interfaces between people and computers. Recently, the trend has been to bring the digital and physical worlds together. Mark Weiser's vision (Weiser, 1991) articulates technologies that weave themselves into the fabric of daily life. The display technologies and electronic interfaces becoming more ubiquitous is one such direction. This thesis however, is an attempt to reappropriate the natural world around us as interfaces. Chapters 4 and 6 show possibility of sensing inputs and

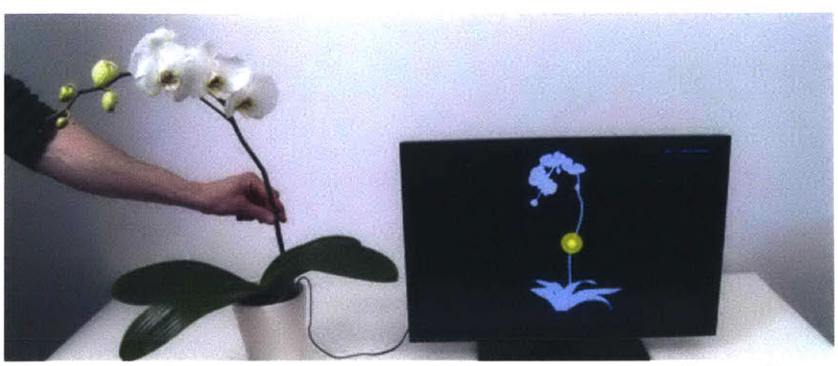

Figure 3.7 Botanicus Interacticus: Detecting where the user is touching a plant. Credits: Disney Research

triggering outputs through a merged synthetic circuitry or new symbiotic associations with plants.

Figure 3.8 Infotropism: Using light response behavior of plants to show contributions of recyclables or trash (Picture: Holstius et al.)

A few HCI researchers have shown examples with electronic sensing technologies around the natural world. Botanicus Interacticus (Poupyrev, 2012) is technology to make expressive plants. A single electrode is placed in the soil with a frequency sweep program that detects when/where an individual is touching a plant.

To achieve pleasing/unobtrusive designs, researchers have attempted to use plants as information displays. Infotropism (Holstius, 2004) is living plant display that informs individuals about relative contributions to recyclables and trash. Mossxels (Kimura, 2014) uses blocks of moss called Racomitrium canescens and is able to do slight a change in appearance by controlling humidity on patches.

For contextual information representation such as weather, water potential or surroundings, plants and their leaves are a good estate. With their flexible electrolumiscent displays technology, PrintScreen (Olberding, 2014) showed examples of such digital displays on plants. Another instance of attaching external electronic devices to plants is EmotiPlant (Angelini, 2016) where researchers put arbitrary sensors on plants for interaction with older adults. 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.

# 4. Phytoactuators

*[…] "if all the ideas of Charles Darwin were accepted, we would look at plants as excitable creatures instead of vegetables we're taught at school" […]*
*Paul Simons, The Action Plant*

In this chapter, I propose a new bioactuation technique to control movement of plants from a digital interface. When a user presses the regions of a plant in a custom software, they are electrically stimulated to which the leaves or stems produce their natural movements. This experiment was an initial impetus for a direct digital connection with the plants and an inspiration for a digital-plantbio bridge at large.

## 4.1 Expressive Movements by Plants

It has largely been considered that plants are immobile living organisms always stationary in their habitats or gardens. However, plants do exhibit 'animal-like' movements as first observed by Darwin. His treatise 'The Power of Movement in Plants' (Darwin, 1897) described movements from circumnutation in seedlings, sleep or circadian rhytm actions, tropic responses to movements of climbing plants. Some of these plants have special movements for catching prey, defense, pollination or to optimize light gathering.

The daisy chain of plant movement works by a plant receiving an external (environmental) or internal (hormones) stimulus, relaying signals to motor cells followed by the final movement. The cells driving these movements are unique to each plant. From our daily

Figure 4.1 Clockwise from top left. Arctic Poppies tracking the sun and moving through the span of the day. A Maranta Plant's leaves are flat by the day and folded up as the day comes to an end. A Tulip plant opens and closes as the clouds pass above it. Hammer Orchid's (Credit: One Minute Physics) labellum moves with momentum of the wasp landing on it to pollinate

lives, we are familiar with the actions such as Tulips closing with clouds above them, Hammer Orchids striking pollen on insects, Prayer plant opening at night or Sunflowers rotating to face the sun.

## 4.2 Biohydraulics and Timescale

Plants have evolved several mechanisms for organ actuation. Specialized motor cells act as hinge at joints to enable movement of parts. They help in opening or closing the leaves in proportion to the light intensity (*nyctinasty*). On the other hand, rapid movements are primarily accomplished by osmotic influx and efflux of water in the cells. The cells initially turn turgid by regulating the internal concentration of potassium ions, followed by water loss to return to normal positions. Nastic or sleep movements can take place in a few hours or between day and night, whereas rapid movements can take place in a few seconds.

## 4.3 Nervous Plants – Venus Flytrap and Mimosa Pudica

The Venus Flytrap (*Dionaea Muscipula*) and the Sensitive Plant (*Mimosa Pudica*) are one of the few plants capable of rapid movements. The Flytrap is a carnivorous plant that catches its prey the with a trapping structure at the end of its leaves. The hair-like structures inside the leaves act as triggers. When an insect touches the hair for the first time, a timer is started following which a second contact within 20 seconds shuts the trap. If the prey was missed, the plant reopens the trap in a day or so.

Figure 4.2 a) Mimosa Pudica's compound leaves fold when touched or shaken, b) Dionaea muscipula or a Venus Flytrap with a trapping structure triggered to close by tiny hairs on its surface

A similar reversible movement happens in Mimosa Pudica. On a slight touch or shake, the compound leaves droop and fold inward. This behavior is attributed to plant's mode of preventing itself from harm. Owing to their fast response times, I use the above two plant systems for this experiment.

## 4.4 Phytoactuators

### 4.4.1 Action Potentials

Both Mimosa and Flytrap have long and clear actions potential, similar to electrical signals in the animal nerves. These potentials, observable through standard electrophysiology initiate the movement response. On a mechanical touch to the leaves, the chloride ($Cl^-$) and potassium ($K^+$) ions move out of the cells (Scorza, 2011) causing an osmotic imbalance. The cell vacuoles hence lose water thus causing movement.

### 4.4.2 Bioactuation

For my investigation, I flipped the order of signal and response in the plants. Silver electrodes (Refer Appendix B.5 for bleached Ag Electrodes preparation) are attached to the parts of the plants where ionic imbalances are observed. For a Venus Flytrap, this is the mid-rib and mid-leaf. On a Mimosa plant, this is usually the top and bottom of petiole or the part joining the primary stem. A custom designed circuit sends a stable 5V or 3V direct

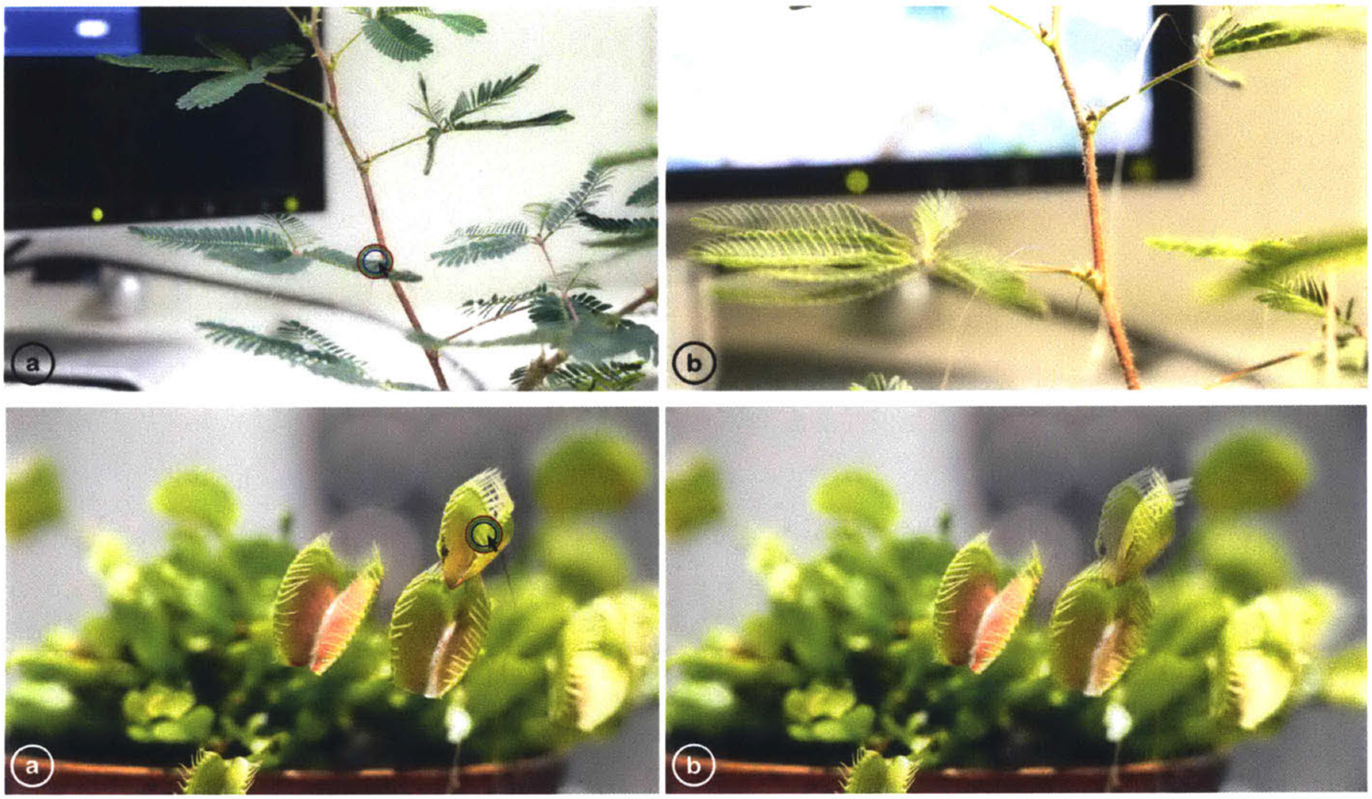


Figure 4.3 The top and bottom left are screen captures from an openFrameworks application with live camera view of the plants. The user clicks on a particular lead when the signals are sent through the attached electrodes. The photos of top and bottom right show the actuation being triggered in a live plant. Notice the overlay of initial and final position.

current signal for 3 seconds. The electrical potential between the two electrodes is interpreted as biochemical potential difference (similar to their own ionic imbalance reactions) stimulating the movement in the plants.

As an extension, an openFrameworks application (Screenshots: Figure 4.3 Top and bottom left) was developed with known position of electrodes and a live view of the plants. When a user clicks on an electrode location, the corresponding electrodes are stimulated triggering the movement in the plants. An overlay of initial and final positions of the leaves in Fig 4.3 Top and bottom right shows digitally triggered actuation output. A timeline of the movement is presented in the figures next.

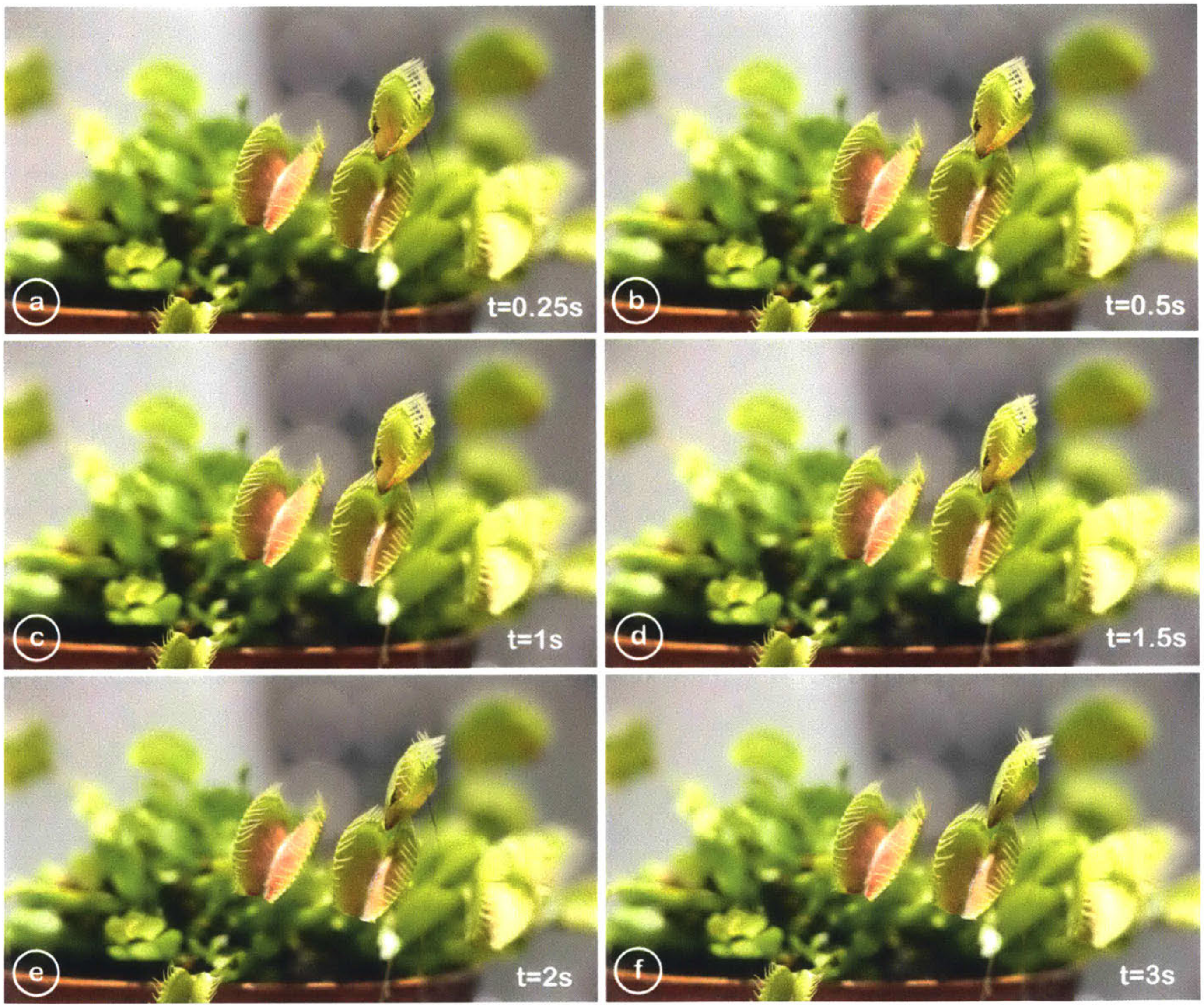


Figure 4.4 A timeline of movement after the user triggers a leaf actuation. A Venus flytrap closes in approximately three seconds after the electrical trigger.

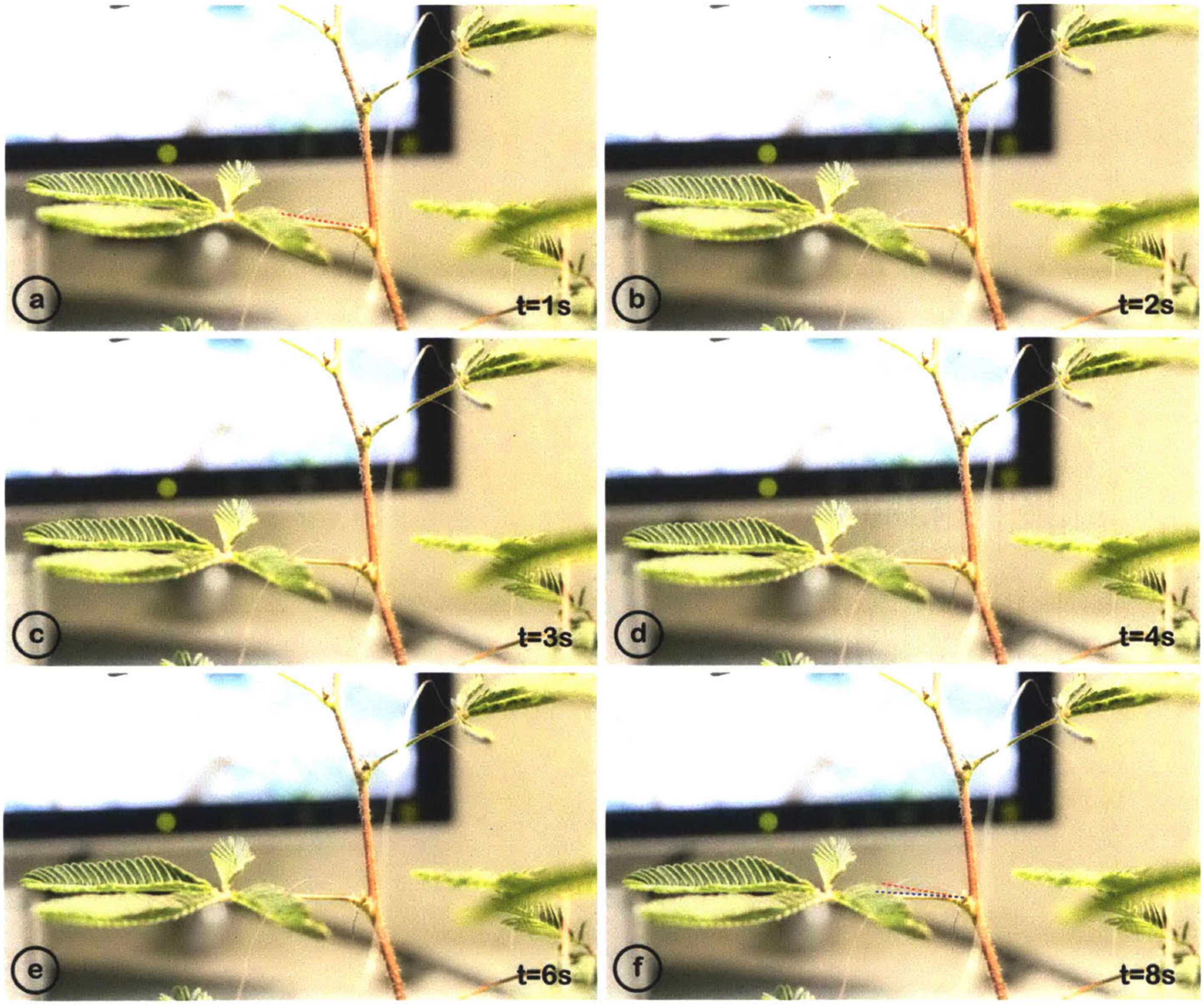


Figure 4.5 A timeline of movement after the user triggers a leaf actuation in Mimosa Pudica. Notice the difference in movement speed from the previous plant as this takes approx.. 8s to move to the new position. In addition, a higher voltage droops the branch lower and closes its leaves (not shown here)

### 4.4.3 Hardware

Ag/AgCl electrodes are prepared by bleaching pure (0.999) silver wire. With an equilibrium between Ag and its salt AgCl, the electrode functions as a reversible redox electrode. This helps in measuring extracellular potential in plants or converting electrical to bioelectrochemical potential.

A current limited low voltage circuit (Refer to Appendix B.1) completes a circuit through a plant's leaf when the microcontroller digital signal is enabled. A stable 3V or 5V, isolated from dangerous voltages creates a potential difference in the leaves or stems causing them to actuate. This is essentially emulating the process after a mechanical stimulation occurs in a plant's real environment.

## 4.5 Proposed Interfaces

Such input/output plants can possibly have interactive applications as well. Some plants are already used by people as weather indicators as predictors for rain when they are closed. Such movements can be triggered in the houseplants to show information. In addition, the movements could be used a direct expression from the plants while watering, e.g. actuation to communicate optimal water quantity etc.

# 5. Elowan – A Robot-Plant

*[...] "what I have really said is, that all are not as perfect as they might have been in relation to their conditions; and this is shown to be the case by so many native forms in many quarters of the world having yielded their places to intruding foreigners" [...]*
*Darwin, Origin of Species*

The enduring evolutionary processes change the traits of an organism based on the fitness with the environment. In the recent history, humans domesticated the plants selecting the desired species. A few became house plants while others fit for agricultural practice. From the natural habitats to micro-climates, the environments for the plants have significantly altered. As humans, we rely on technological augmentations to tune our fitness to the envrionment. However, the acceleration of evolution through technology needs to move from a human centric to a holistic nature centric view. Elowan is one such example - a cybernetic lifeform, a plant in direct dialogue with a machine. The plant is interfaced through its own internal signals with a robotic extension that drives it towards light.

I created Elowan as an initial thought provoking attempt as to what augmented plants would mean. Plants are immobile, they lose water as stomata pores open to photosynthesize and have sparse defense mechanisms. To augment the mobility for a plant, Elowan's robotic base is not a vain accessory but a new symbiotic association. The agency rests with the plants based on its bioelectrochemical signals, the language interfaced here with the artificial world.

## 5.1 Electrical Signals inside Plants

Plants are electrically active systems. They get bioelectrochemically excited and conduct these signals for long distance transmission between tissues and organs. Such electrical signals are produced in response to changes in light, gravity, mechanical stimulation, temperature, wounding and other environmental conditions. These in turn trigger physiological variation such as elongation growth, respiration, moisture absorption etc.

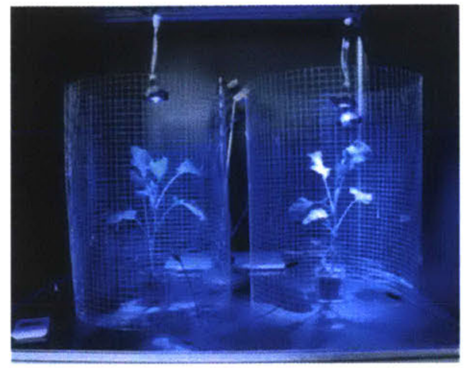

Figure 5.1 Plants in a Faraday cage to prevent any external interference. Here electrical signals are observed inside them with the change of light color. Experiment pictures from the LINV Plant Neurobiology Lab.
Also refer to Figure 2.2 for an experiment of action potentials in Mimosa Pudica

The electrical signals in plants can be divided into three types (Yan, 2009):
**i) Local Electrical Potential (LEP)**: sub-threshold response induced by environmental factors,
**ii) Action Potential (AP)**: induced by non-damaging stimuli (e.g.: cold, mechanical stimuli) and can rapidly transmit over long distances,
**iii) Variation Potential (VP)**: induced by damaging stimuli (e.g.: burning, wounding) and decreases in magnitude as it travels away from the stimulation site.

Light is a vital parameter for photosynthesis in plants (Theil, 1892). Perceiving the variation in the amount of light is hence of significant importance. A dark/light transition triggers stomata opening and vice versa. Researchers have measured surface electrical potential in epidermal and mesophyll regions caused by dark/light transition that leads to cell depolarization (Yan, 2009). These light-on/light-off and reverse transitions are observable as potentials in most of the higher plants. The experimental setup involves surface contact electrodes or metal electrodes inserted into the regions of interest (stems and ground, leaf and ground etc.) The weak signals are then amplified using an instrumentation amplifier with a high input impedance. For the schematics of bioelectric amplification circuit used in Elowan, refer to Appendix B.2

## 5.2 Half-Plant, Half-Machine

The mutation of a plant and a machine results in the composition of a new biomachine. The autonomous system relies on the plant signals to drive a robot.

### 5.2.1 Plant System

All higher plants rely on electrochemical signals to trigger responses to the environment. For this investigation, I chose a *Homalomena* plant owing to its strong electrochemical signals.

### 5.2.2 Robot System

A 2WD Drive Robot (Seeed Studio # 110990061) with an onboard microcontroller (Atmel 328P) was chosen as the plant vehicle.

### 5.2.3 Hybrid System - A Mobility Extension for Plants

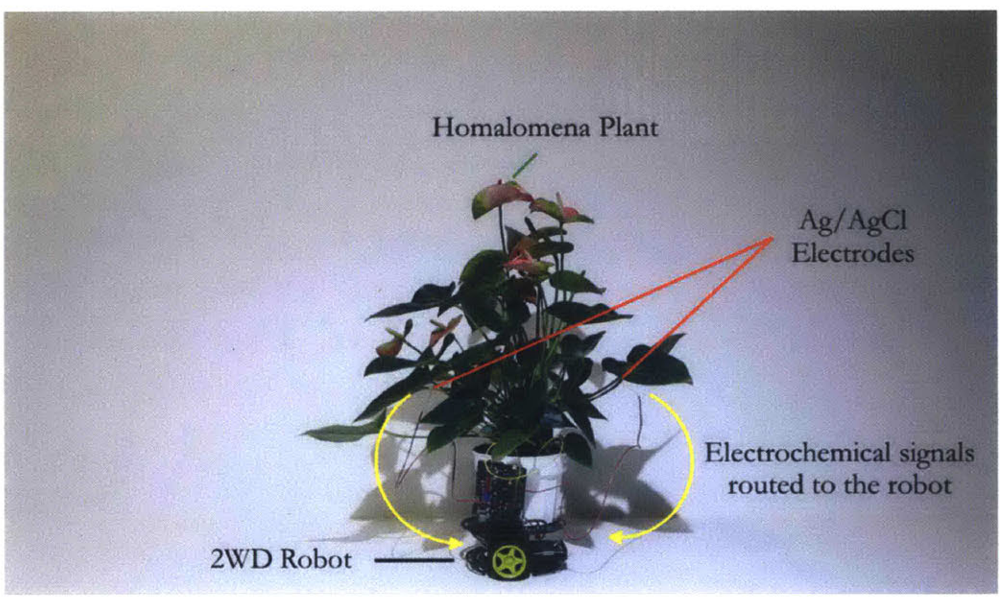


Figure 5.2 An exogenous mobility extension of a plant. Signals are triggered inside the plant on dark/light transition, read through two Ag/AgCl electrodes, further amplified and interpreted as triggers for robot movement.

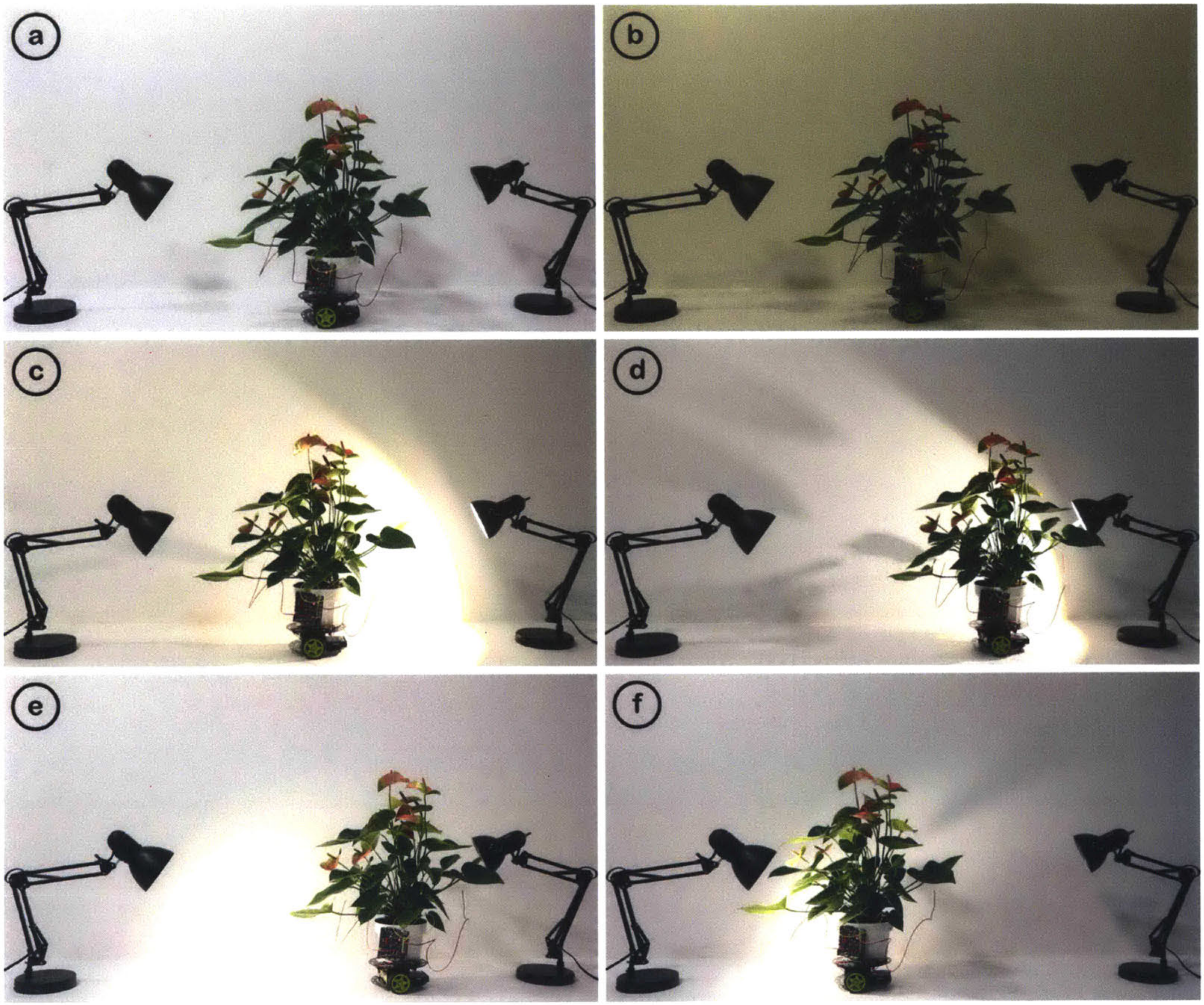


Figure 5.3 Two lamps are placed on either side of Elowan. The lamps are switched on and off manually, triggering transition potential inside the plants. This triggers the robot movement towards either side.

As discussed in 4.4.3, Ag/AgCl electrodes aid in reading the plant signals (owing to their redox property). One electrode is connected at the beginning of a leaf (inserted in the stem) with the other electrode is grounded in soil. The same is done on another leaf to read the signal from the other side of the plant as seen in Figure 5.2.

Two lamps on either side of the plant form the light source(s) for the plant. The signals are generated with a dark to light transition with the following event flow:

Dark to Light Transition > Stoma opens > Depolarization of cells > Signals read in the electrodes

The time between a light turning on and a signal being read is 120-180s. These signals are (peak: 60 mV, time: 1ms) amplified by AD620 instrumentation amplifiers and fed into the robot microcontroller input. Two analog pins continuously poll for the signal and check against a set threshold. A threshold cross on the right invokes the right direction robot movements, whereas a potential read from the left drives the robot to the left.

Such symbiotic interplay with the artificial could be extended further with exogenous extensions that provide nutrition, growth frameworks and new defense mechanisms.

# 6. Planta Digitalis

In the previous chapters, I showed sensing, actuation and physical responses of plants to triggers in the environment. The design of modern electronics encompasses such goals of sensing and displays through silicon or organic materials. For the striking capabilities of self-regeneration and self-powering, plants have systems for water movement, nutrient regulation and energy conversion. A convergent view of merging electronics with the plants could help us harness their unusual capabilities and power new systems for our requirements.

Researchers have previously introduced materials inside the plants for cell observation (Djikanović, 2012), affecting growth or disease resistance (Kanhed, 2014). Recently, Stavrinidou et al. studied polymerization of organic conductive materials inside vascular channels of the the plants (Stavrinidou, 2015). In this chapter, I explore the design space and interaction possibilities of such plants.

## 6.1 Vascular and Electronic Circuitry

Figure 6.1 Benign food dyes expressing color on a white Carnation flower

A large number of land plants have tissues for conducting water (lignified tissue, xylem) and products of photosynthesis (non-lignified tissue, phloem) throughout the plant. These vascular channels draw solutes from the soil through a network of vessels or tracheids. Such distribution is analogous to electronic channels, connections and outputs.

Merging a new synthetic circuitry with the plant's can be one mode of symbiotic association. Hark back to the high school days and most of us have performed experiments with benign food dyes which express their color on white flowers. This forms the basis for the uptake of novel conductive materials in the plant channels. Replacing the food dyes with other materials that do not activate the self-defense of the plants can result in new conductive channels. Based on the material identification with plant channel size (Stavrinidou, 2015), I grew the organic conductive wires (Refer 6.1.1) inside the plants. These were used as specimens for new applications around augmented plants.

Figure 6.2 Stems from a Rose plant in fresh water before experiments

### 6.1.1 Growing Wires

PEDOT is a synthetic organic polymer commonly used in antistatic packaging, solar cells and more. PEDOT-S, a water soluble variant was added to water in which stem cuttings (from locally procured *Rosa Floribunda*) were put for 48 hours. The barks of two specimens were peeled and observed under a microscope for wires up to 30 um thick and 5-8 cm (approx.) long.

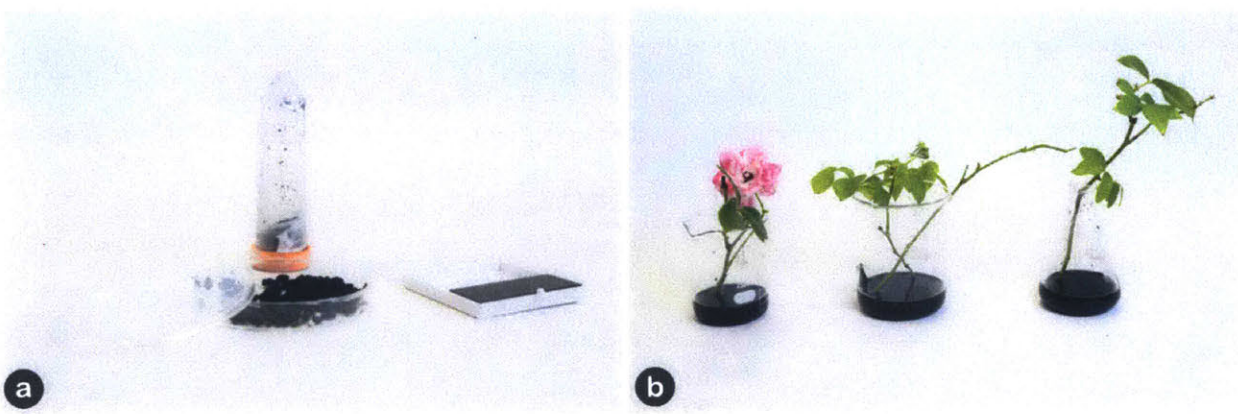


Figure 6.3 a) PEDOT-S in a petridish before the experiment. PEDOT is a thiophene based conjugated polymer that carries positive charges and hence conductive. PEDOT-S and PRODOT were used for this experiment. b) 1:1 solution of PEDOT-S was prepared with water and fresh cut plant stems were kept in it for 48 hours. Followed by the uptake of the material, the solution polymerizes to a hydrogel wire inside inside the xylem channel of the plant. (Refer to Stavrinidou in Bib. For full protocol)

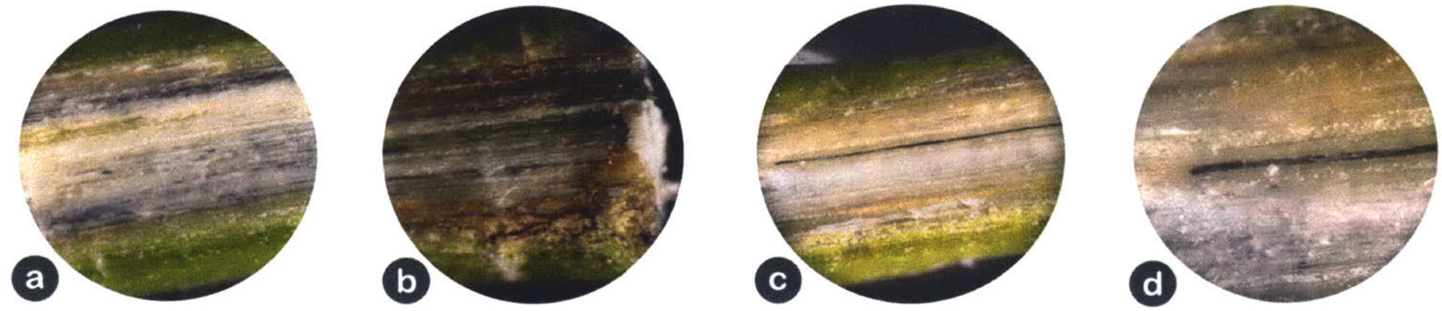


Figure 6.4 Figure shows sections of plants from the previous experiment under an optical microscope. a) and b) show peeled off sections from the stem showing xylem structure whereas c) and d) show sections of the same plant 7cm apart. This was the longest grown wire observed of all the experiments.

## 6.2 Plants as Inconspicuous Sensors

### 6.2.1 Connecting Network Analyzer

Stem cuttings from the wire grown specimens were taken and peeled at two different locations. The longest direct growth was observed to be observed to be 8.2 cm 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. 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.

### 6.2.2 Activity Tracking around Plants

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.

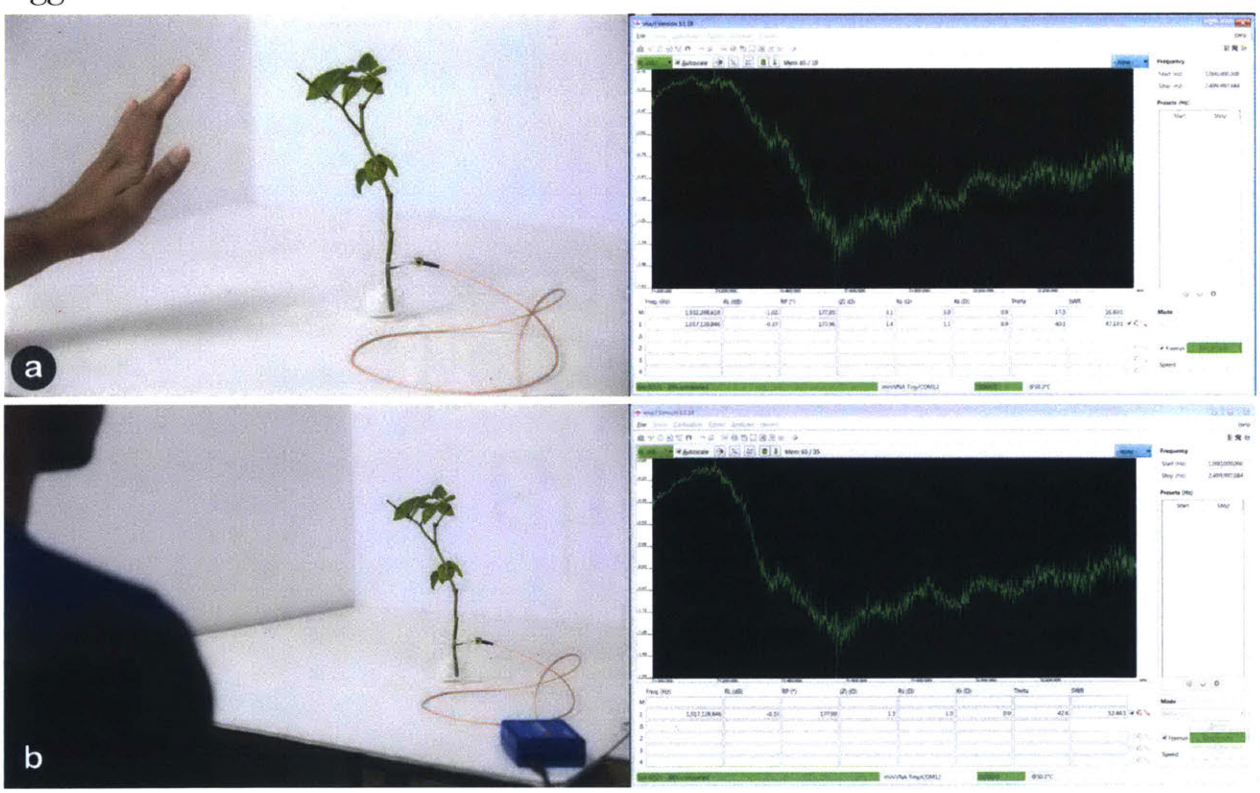


Figure 6.5 A shielded platinum electrode is connected to the grown wire inside the plant. The other end of the electrodes is connected to a SMA wire and further to a network analyzer. This step shows data being logged from miniVNA/J application to a text file for classification later on openFrameworks.

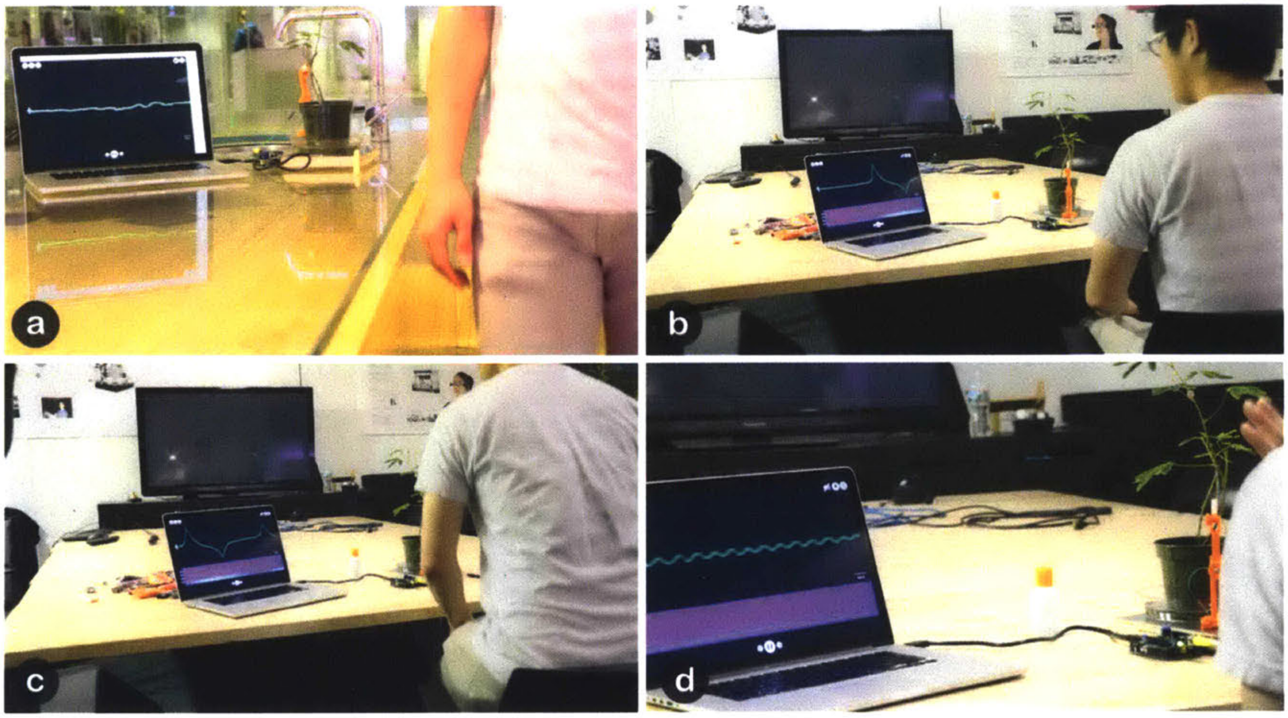

Figure 6.6 Data from the text file is parsed into an openFrameworks application that classifies it into a set of activities. a) to d) show different activities being performed in proximity to the plant which are analyzed to categorize each activity

Figure 6.6 shows the signal data feeding in an openFrameworks application with activities classified with the pattern of interference the user creates around the plant. As can be seen, the patterns of certain activities are distinct making it possible to classify certain cases easily.

The in-vivo wires along with the frequency sweep help engineer antenna-like electromagnetic properties in plants. The interference patterns or coupling with EM waves can thus be used for broader applications in the future.

## 6.3 Design 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. A consolidated design space for such plants with electronic channels is tabulated below.

| Signal Type | Plant Type (x + Vascular) | Possible Application | I/O Modality |
|---|---|---|---|
| Audio Signal | Spiral | Speaker | Output |
| Swept Frequency Electrical | Any | Touch | Input |
| EM | Any | Motion Sensor | Input |
| Potential Difference | Any | Environmental Sensor | Input |
| Potential Difference | Nastic Movements | Actuation | Output |
| Potential Difference | Anthocyanin Pigments | Color | Output |

Table 1 A Design Space of plants with in-vivo conductive channels. Based on plant morphologies, signal through the conductive channels and other unique plant characteristics, several applications of I/O modalities are possible.

# 7. *'In-Planta'* Lead Sensing

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. The precedents follow from agricultural biotechnology and nanomaterials to make plant's resistant to diseases, enhance their nutrient absorption and more.

In this chapter, I show heavy metal (Lead, $Pb^{2+}$) sensing capability inside the plants. 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.

Several nanomaterials and their effects have been studied on plants (Masarovičová, 2013). Carbon-based materials, which I will discuss next, form a stable platform for a variety of applications.

## 7.1 Carbon-Based Nanomaterials

### 7.1.1 In Agriculture

The research of carbon materials on plants trickled from their use first on mammalian cells (Cherukuri, 2006). In plants, materials as Fullerene ($C_{70}$) and Carbon Nanotubes (CNTs) have been shown to increase water retaining capacity, biomass and fruit up to ~118% (Husen A. , 2014). These can be taken up by the plant through the roots and distributed in the aerial parts in the following order:

Seed > Root > Stem > Leaf

While $C_{70}$ increases hydrophilicity, CNTs have been shown to penetrate the seeds and plant cells. While plant cells might not take up certain molecules alone, binding with CNTs can help uptake through endocytosis (Liu, 2009).

### 7.1.2 Carbon Nanotubes / CNTs

Carbon Nanotubes are one-dimensional nanoscale materials composed of carbon atoms. They can be single walled or multi-walled. A Single Walled Carbon Nanotube (SWNT) can be considered as being formed by rolling a piece of graphene to create a seamless cylinder diameter of 0.4 - 2nm. A Multiwalled Carbon Nanotube (MWNT) comprises of several layers of graphene cylinders that are concentrically nested.

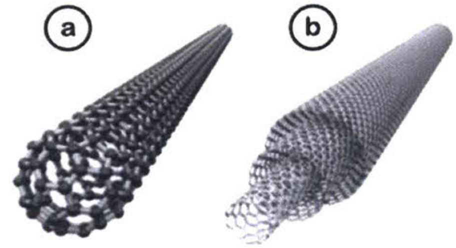


Figure 7.1 Structure of Carbon Nanotubes a) Single Walled, b) Multi-walled

### 7.1.3 CNT Sensors

CNTs themselves do not have an intrinsic ability for selective binding and recognition of analytes. They are often functionalized with molecular probes that bind to specific targets. The surface of CNTs can be easily functionalized through π-π stacking or hydrophobic interactions. This is often non-destructive for conjugated electron structure of CNTs and is known as non-covalent functionalization.

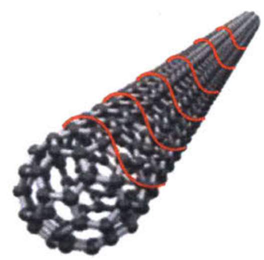

Figure 7.2 Structure of Carbon Nanotubes after functionalization

CNTs can produce fluorescence (NIR) or act as quenchers for a large range of flourophores adsorbed on the surface. Flourescence occurs by excitation at the second van Hove absorption with emission at the frst van Hove emission. Quenching on the other hand can occur through energy transfer from flourophores in close proximity to the walls. This general strategy allows design of large number of 'in-vitro' and 'in-vivo' sensors.

## 7.2 Design of '*in-planta*' CNT $Pb^{2+}$ Sensors

The levels of $Pb^{2+}$ in drinking water and the environment are to be closely monitored owing to its detrimental effects on the human body. Contamination sources can be industrial wastes, paints, alloys and more.

### 7.2.1 Traditional $Pb^{2+}$/Lead Sensing

Sensing $Pb^{2+}$ isn't an easy off-the-shelf electronic sensor work. Sophisticated instrumentation and a number of days are required for such analysis. Current techniques include atomic absorption spectrometry (Shibata, 1996) and electrochemistry (Stoica, 2000).

### 7.2.2 Sampling through Plants

For a continuous self-powered sampling from the ground, water extraction due to negative pressure or transpiration in plants is an effective approach. Strano et al. modelled the plant hydraulics and tested in-vivo sensors for detection of nitroaromatics in plants (Wong, 2017).

### 7.2.3 Design Scheme of SWCNT-Pb2+ sensors

Lead(II) sensors capable of providing immediate optical readout through various molecular probes such as proteins (Chen, 2005), peptides (Deo, 2000) and ligands (Métivier, 2003) have been proposed. CNT sensors from Strano et al. provide '*in-planta*' readout for nitroaromatics.

I use the DNA cleavage approach by Yao et al. (Yao, 2011) but for in-vivo detection in plants. $Pb^{2+}$ catalyzes cleavage of DNAzyme which releases the single stranded DNA (ssDNA). ssDNA has high affinity towards SWNT walls and gets adsorbed easily. In contrast, double-stranded DNA (dsDNA) has significantly less attraction due to stiffer structure and a negatively charged backbone. If ssDNA was labelled with a flourophore, SWNT will quench the fluorescence due to the proximity between ssDNA and outer walls. Such differential binding and quenching property is commonly used as signaling tools for biological sensors.

I use '8-17 DNAzyme' for *turn-off assay* where 5'-end of strand is labelled with a quencher and 3'-end with a flourophore. In presence of $Pb^{2+}$, the dsDNA is cleaved to ssDNA which binds more strongly to SWNT walls thus quenching the flourophore. The reduction in fluorescence is proportional to the Lead(II) concentration.

### 7.2.4 Sensor Preparation

Carboxyl functionalized SWNTs (SWNT-COOH, dia: 2-4nm, length: 50-100nm) were purchased from Sigma-Aldrich. Oligonucleotides were purchased from Integrated DNA with sequences as mentioned in Table 1 (ref: Yao, 2011)

| Name | Sequence |
|---|---|
| Pb2+-dependent enzyme | 5'-CAT CTC TTC TCC GAG CCG GTC GAA ATA GTG AGT -3' |
| Cy3 labelled substrate | 5'-/cy3/-ACT CAC TAT rA GG AAG AGA TG -3' |
| Complementary strand to 17S | 5'-CA TCT CTT CCT ATA GTG AGT-3' |

Table 2 Sequence of DNA molecules used in the assay (Table from Yao et al., 2011)

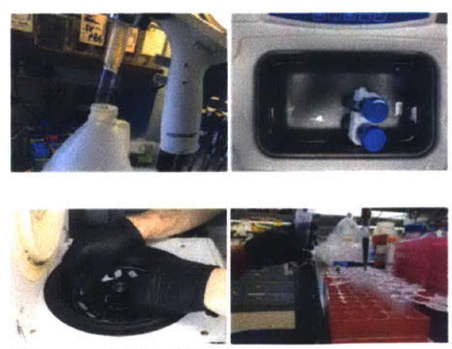

Figure 7.3 CNT Sensors functionalization through mixing, sonication and centrifuging

### 7.2.5 8-17DNAzyme

For dsDNA, 17E was mixed with an equimolar amount of Cy3–17S in the reaction buffer (500 mM Tris-acetate and 500 mM NaNO3, pH 7.8). This mixture was denatured at 98 C for 2 min and slowly cooled to 4 C over 20 min.

### 7.2.6 SWCNT preparation

SWCNT-COOH solutions were prepared at a concentration of 1mg $ml^{-1}$. The solution was sonicated in a bath sonicator for 2 hours to disperse the CNT bundles. The result was then mixed with the previous DNAzyme at 1:1 v/v ratio.

### 7.2.7 In-Vivo Delivery

A Spathiphyllum plant system (8 weeks old), normally used as a houseplant was chosen for testing the sensors to show the applicability in homes and other environments. The plant was purchased from a local shop at 6 weeks old, following which the roots were rinsed and transferred to water culture (DI Water). A needleless syringe was used to do infusion of sensors (Huang, 2011) through the abaxial side of the leaf. The leaf was cleaned of any remaining assay on the surface

Figure 7.4 Leaf infusion of oligo-functionalized CNTs through the abaxial side of the leaf

was left standing for an hour before detection experiment.

## 7.3 Detection Scheme

### 7.3.1 Experimental Setup

The excitation wavelength for SWCNT solution was 535nm as measured previously with a spectroflourometer. This was chosen for this experiment owing to low absorbance of the plants between 500nm-600nm wavelengths.

For a non-specialized digital detection setup, I use a Raspberry Pi with a full spectrum camera. A long pass filter of 600nm (ThorLabs FEL600) is placed in front of the camera. A laser laser diode of 532nm (ThorLabs DJ532-10) is used to excite the dye labelled dsDNA and CNT mixture in the leaf and get the fluorescence output.

Figure 7.5 Flourescence and subsequent is observable in visible domain. RPi digital detection aids long term observation and logging.

### 7.3.2 Introduction of Pb2+ ions

20uL of Pb2+ metal ions are introduced in the beaker using a micropipette.

### 7.3.3 Output in 2h

Following introduction of $Pb^{2+}$ ions, the fluorescence output is quenched due to release of ssDNA and its binding with the CNT walls. The following pictures show the time resolved output.

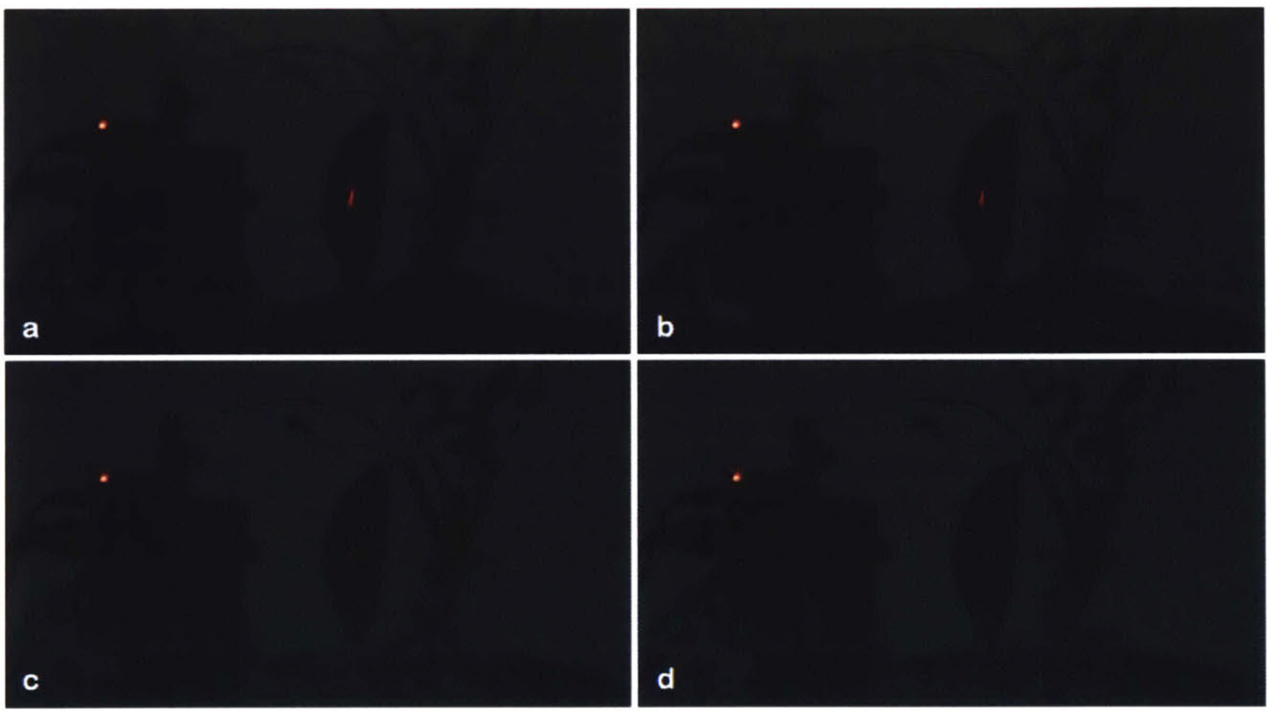


Figure 7.6 Figure shows CNT sensors producing fluorescence when shone with 550nm. Right after introduction, quenching of fluorescence id observed in-vivo, a=15min (100% intensity), b=30min (80%), c=100min (20%), d=150min (Full quenching)

## 7.4 Discussion

**Sensor Design:**

The strategy of such sensor design is general and applicable with other nanomaterials such as Quantum Dots. The molecular probes can be designed using aptamers, polymers, ligands with different strategies such as turn-on, spectral shift and more.

**Applicability:**

Such an approach can be useful at home detection of lead in water. Sensors for detecting other elements can also be deployed in industrial or nuclear towns for continuous monitoring.

These could also be used in the fields to screen bacteria with an order of magnitude higher detection and increasing response time (e.g.: Citrus bacteria in the crops of Florida)

Remote sensing connected with such outputs such as aerial or satellite monitoring can be potentially useful across spatial and temporal scales as opposed to the current approaches.

# 8. Automated 'Arbortecture'

Figure 8.1 Living Root Bridge in East India (Source: Wikipedia)

The French architect, Le Corbusier once described domestic buildings as 'machines for living in' (Corbusier, 2007). The field of architecture has drawn inspiration from the final form of living things. However, the processes that power such growth are of equal significance. Redirecting the morphogenesis processes to produce living structures can lead us to a new self-growing, self-repairing architecture. Examples of such structures have existed for many years and have recently been adapted to new visions.

Figure 8.2 FabTreeHab: Hypothetical ecological home design with growing trees

The ancient root bridges (Myers, 2012) in Eastern India are built by manually training the pliable roots of trees across the river streams. Due to its self-repairing (*self-renewing, self-strengthening*) attributes, the estimated lifetime of such structures is hundreds of years in comparison to concrete structures. The vision of FabTreeHab (Joaqim, 2008) is based off on these paradigms, with a vision to grow residential accommodations from trees that remain living and integrated within the ecosystem.

In this chapter, I introduce automated plant shaping using robots that live on plants. This new symbiotic initial steps for Arbortecture (Chithra, 2015).

Figure 8.3 Output of sunflower's directed growth. Trained was automatically done with a robot on stem and directing through on-board lighting

## 8.1 Traditional Shaping Practices

For a long time, artists have used living trees and other plants as media for structures and art, a practice known as tree shaping. They employ manual techniques such as framing, pruning, grafting in common with artistic agricultural practices of pleaching, topiary etc. The results range from purely aesthetic to functional outputs such as grown furniture or architecture (living chair, arched trees etc.)

Figure 8.4 Trees as medium to create art. Figure shows trees shaped through framing or grafting for sculpture or living furniture

## 8.2 Tropic Movements

Plants have morphogenetic plasticity (Friml, 2003) and grow or orient their structures to gather optimal energy. These phenomena referred to as tropisms, can occur with stimuli of light, gravity, contact and more. Such movements towards or away from a stimulus are often exploited in horticultural practices to train plants. Commonly available Lucky Bamboo (*Draceana Braunii*) is grown in boxes with holes for light to come in from a single direction. The boxes are rotated every few weeks to achieve a spiral growth. In the following sections, I will discuss the mechanisms behind common tropisms that could be exploited for plant shaping. Following this, I present robots that shape plants using photo and gravity responses.

### 8.2.1 Phototropism

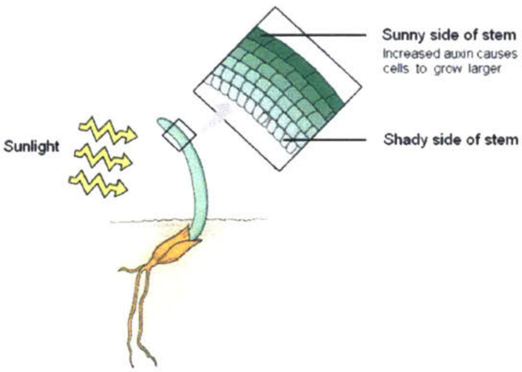


Figure 8.5 Phototropism: Growth of plants towards light stimulus. Auxin gradient occurs with more on shaded part of the plant. The cells in this region elongate to cause the plant to curve.

Phototropism is the growth response of plants in response to lateral changes in light intensity. The reaction is a directional curvature caused by changes in cell elongation rate across the bending organ. This happens because of the auxin gradient, a plant hormone that regulates many growth and behavioral processes.

With the change in the direction of the light source, the signaling molecules in the plants activate several genes that change hormone gradients. Auxin is thus more concentrated towards the shaded side causing elongation of cells leading plants to a curvature towards the light source.

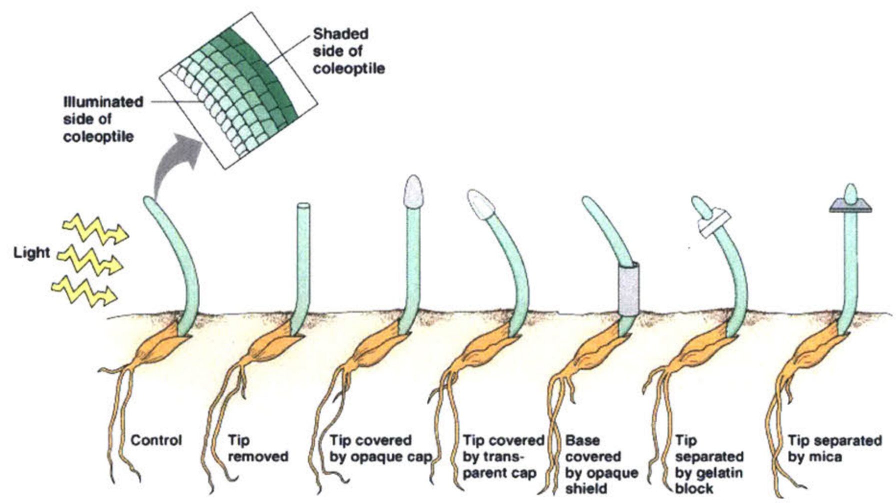


Figure 8.6 The top of a phototropic responsive plant is known as coleoptile and the curvature occurs at its middle portion. Figure depicts how a plant stopps to curve when the tip is covered, cut or separated. (Credits: Pearson Education)

Figure 8.7 Curvature of a 2 week old plant in our greenhouse towards a grow light

The tip of the plant, cleoptile is necessary in this light sensing. Photoreceptor proteins are highly expressed in the upper region of cleoptiles and the middle region of this area is where the shoot curvature occurs. The following figure shown the behavior when the tip of a plant is covered or cut, which prevents any curvature even with the change of the light source direction.

### 8.2.2 Gravitropism

Plants are biological gravity-sensing devices that contain molecular receptors to perceive information generated by displacement of organs. All higher plants and other organisms exhibit a growth movement or turning with roots growing in the direction of the gravity while stems growing opposite to it. This process ensures proper positioning of the leaves for efficient photosynthesis and gas exchange.

The gravity susceptors in higher plants are dense amyloplasts (Haberlandt, 1900) that sediment in specialized cells. The tilting of a plant leads to sedimentation of amyloplasts to new physical location. This activates receptor signals that then trigger organ-tip curvature. On the whole, the root cap perceives the change in root tip orientation whereas auxin gradient guides the gravitropism in shoots.

Figure 8.7 The output of a Bonsai plant manually trained by changing gravity over months. (Credit: Peter Del Tredici, MIT)

### 8.2.3 Thigmotropism

In twining plants, a mechanosensory response to touch stimulus helps in coiling around solid object. This phenomena, know as thigmotropism occurs due to unilateral growth inhibition (Jaffe, 2002) wherein growth rate on the side of the stem being touched is slower than on the opposite side. The resultant growth is to attach around an object touching the plant. I chose to mention here thigmo responses out of many other tropisms because it has an interesting override property over light and gravity and follows scaffolds even though the direction might be opposite to other two stimuli. This potentially can also be harnessed in auto-shaping the plants.

## 8.3 Sunflower Plant System

For robotic phototropic shaping, the following properties were desired from a plant system:

1. Strong stem (>1cm lignified diameter) with ample pliability when not lignified
2. Fast growth (> 2ft growth per month) to test iterations within project timeline
3. Single stem with minimum off-shoots or branches
4. Positive and regular phototropic response

Pliability, motion dynamics and growth rate of a plant play a crucial role in the design of the symbiotic robot. The following plants were short listed with the above properties:

i. Single cane Bamboo (e.g. Moso, Temperate bamboo)
ii. Helianthus Annuus (Perennial Mammoth Sunflower varieties)
iii. Peppermint Stick Giant Reed (>1cm cane diameter, available as grown plant),
iv. Arundo Donax (>1cm cane diameter, available as grown plant)

While a bamboo plant system (timber variety) is ideal for fast growth and use in architectural structures, these have to be grown for a certain number of years before lengthening plus lignification process starts. For our purposes and timeframe, the next on list – perennial sunflower varieties fit the requirements. Two varieties of sunflower were chosen for the directed growth:

a) ProCut Gold (Johnny's Selected Seeds #1896)
    Hybrid Status: F1
    Days to Maturity: 55 to 60 days
    Height: 60"-72"

b) Russian Mammoths (Natural *Helianthus Annuus*)
Days to Maturity: 60 to 90 days
Height: 96"-132"

Most plant sciences experiments entail isolation of all factors before a single variable can be studied. For shaping a plant with a phototropic robot (robot with light source for directed growth), the design was limited to an indoor system. An outdoor setup would entail higher intensity light sources and averaging between the natural and artificial light source.

### 8.3.1 Propagation

Two batches of sunflowers were tested for shaping.

**Batch I (ProCut Gold F1):**
ProCut Gold F1 sunflowers were started from seeds in propagation trays. Well drained soil media (Black Gold Potting Soil, Black Gold Perlite 2:1 ratio) was used for germination and growth. The plants were transferred at the beginning of Week 3 to Bloem planters (6.5 x 7.4 x 7.4 inches). Photoperiod of 16h light, 8h darkness was maintained. (Grow light: TaoTronics 36W for each plant with led wavelength (660 nm:630 nm:460 nm) ratio 3:7:2; Average distance from plants 8 inches). The plants were then taken out of the greenhouse, robots mounted on the stems at Week 5 and grown for additional 3 weeks.

**Batch II (Russian Mammoth):**
Russian Mammoths were purchased from a local farmer's market already grown for 4 weeks. These were transferred to tom pots (24 x 12 x 12 inches) and put under the grow lights for additional 2 weeks before the bottom 1ft regions of the stems were lignified. Photoperiod of 16h light, 8h darkness was maintained. (Grow light: Viparpsectra 300W R=32.2%, G=18.5%, B=49.3%; Average distance from plants 8 inches)

The plants were subsequently removed from the greenhouse and the robots were mounted for growth for an additional 5 weeks.

Temperature in the greenhouse was maintained at 74F for both batches with humidity at 50%.

### 8.3.2 Light response

Young sunflowers do exhibit phototropism unlike mature flowerheads that always face east. Usage of more red in the spectrum (with the right photoperiod) is floral inducing and more of blue incudes vegetative growth. Shortage of blue in the initial growth leads to long but floppy stems.

It is a common knowledge among growers to use 50W of light per sq. m. for optimal growth. This is taken into consideration in the lighting design of the robot.

### 8.3.3 Lignification Process

Lignification is a process in higher plants to strengthen the vascular body. The tissues become structurally stronger due to a class of organic polymers called lignin, especially in the bark to lend rigidity. While composition and lignification timeline varies in each plant, Helianthus (varieties used in this experiment) lignify the cell walls for support as it grows in height approx. beyond 2ft. Perennial var. Helianthus, in this experiment can grow 24"-48" in 4 weeks with estimated half the length getting lignified.

### 8.3.4 Growth Timeline

The timeline for Helianthus growth depends on the variety and the environment. The plants go from emergence to vegetative growth followed by budding, flowering and maturation. The gain in stem length does not occur once the plants reach the reproductive stage i.e. budding and flowering. ProCut F1 Hybrids have a flowering timelines of 60 days in comparison to Russian Mammoths that flower in 90 days.

## 8.4 Training growth with light

The vision of 'Automated Arbortecture' is to direct the morphogenesis of plants to build structural frameworks and artefacts integrated in our ecosystem. The current approaches rely either on manual processes or directing the processes with scaffolds around the growing system. A self-building architectural process cannot start to be sustainable if it relies on a pre-built architecture around it. This is where the decision of a symbiotic robot weighs in – a climbing robot that lives on a plant, powers a plant's growth and is able to direct it.

### 8.4.1 Phototropic robot

A phototropic robot uses a **plant as a scaffolding** with an ascend/descend mechanism and light(s) to power a plant's growth. To test this hypothesis, I performed sunflower shaping in two subsequent batches. Each batch had four plants with a phototropic robot shaping each plant.

### 8.4.2 Overall design

The primary components for the phototropic robot were **locomotion** (for ascend/descend on the plant) and **lighting** (to grow a plant including the right spectrum/photoperiod for vegetative growth).

### 8.4.3 Design considerations

In a greenhouse setting, the lights are at a minimum distance of 8" from the plant tips to maintain good intensity but prevent burns. Since the high intensity lights in a greenhouse are for a batch of plants at once, a single low intensity light for a single plant can be brought a closer (4-6" while still taking into account the distance to maintain for proper distribution on a larger area of the plant for efficient photosynthesis.

For this purpose, ultra-low weight (5g), high-power LEDs were selected [Cree High Power LED (17.85 mm x 17.85 mm x 1.7 mm), Color Temperature 6500K, Power Rating 57W; Mouser 941-CXA18300N00U465F]

To maintain operating efficiency for weeks of operation, heat sinks (5g) with Natural Thermal Resistance of 14.3°C/W [Digikey: 345-1140-ND, 21.00mm x 21.00mm] were selected. To reduce any further onboard weight of fans for heat sinks, heatsink airflow was decided for onboard cooling with 1/16" tubes dispersing air through a separate compressor. The lights were decided to be mounted on 0.125" dia, 8" long carbon fiber tubes from the robot.

Stem thickness of > 0.75cm was assumed for locomotion design. The weight constraint was placed at **50g** (excluding wires or tubing), a fibrous sunflower was manually observed to sustain this without the stem bending or tissue rupture after a time. With the above

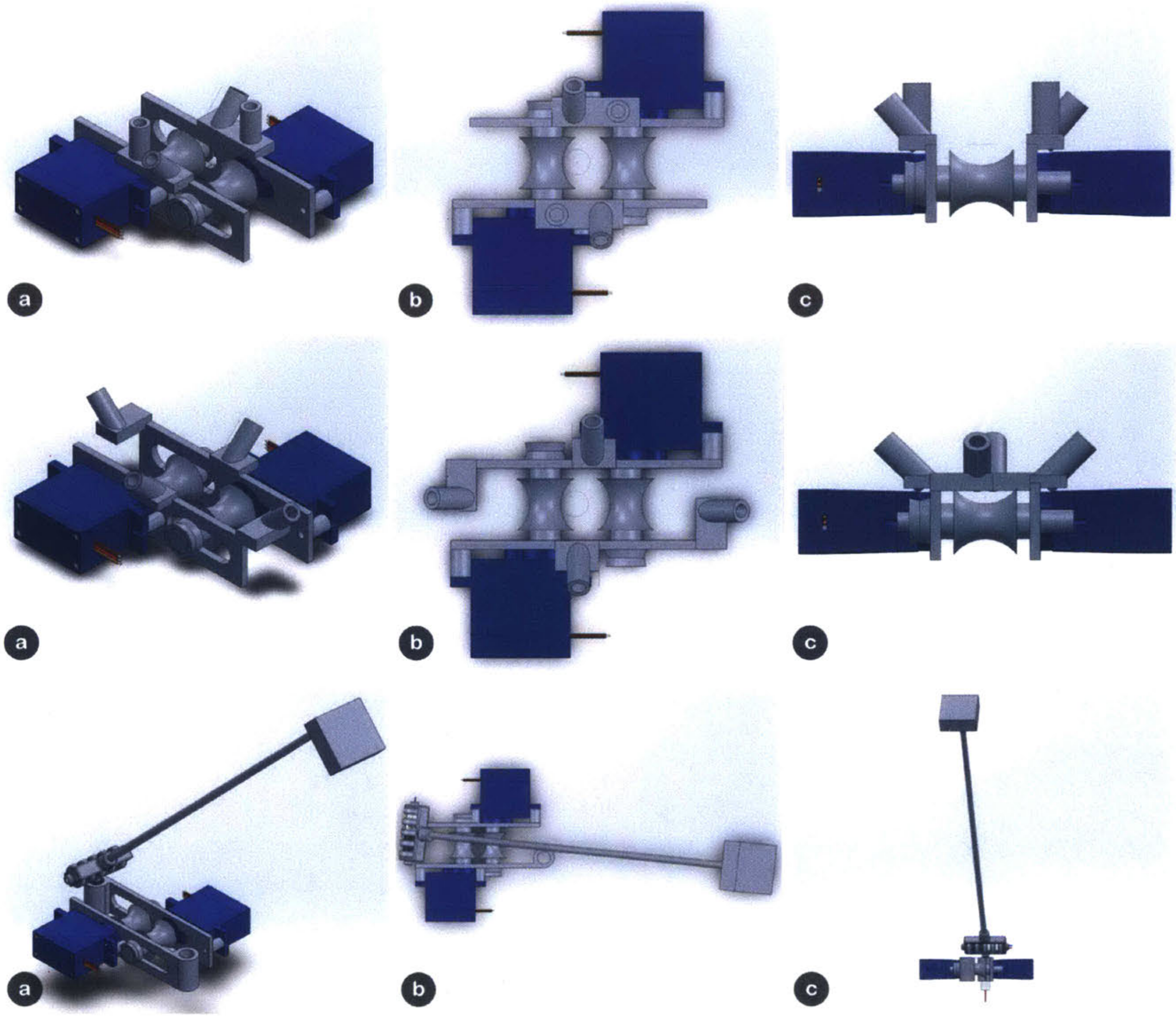


Figure 8.8 Each row shows an iteration of the mechanical design for the plant climbing robot. Row 1 design features three lights 7" inches away from the fixture, Row 2 features four lights arranged in a circle above the robot, Row 3 is a version with a robotic arm controlled through micro-DC motors.

decisions, the following mechanical design was prepared for the robot.

### 8.4.4 Mechanical Design

The redirection of the growth is dependent on the redirection of the light position. Two iterations for the robot were designed in SolidWorks and implemented:

1. Robot with three onboard lights for left, right and mid growth direction.
2. Robot with four onboard light in circular region above the robot for spiral growth if the lights switch in regular fashion

An additional CAD design was made for micro dc motors controlling a micro robotic arm above the robot for the light position.

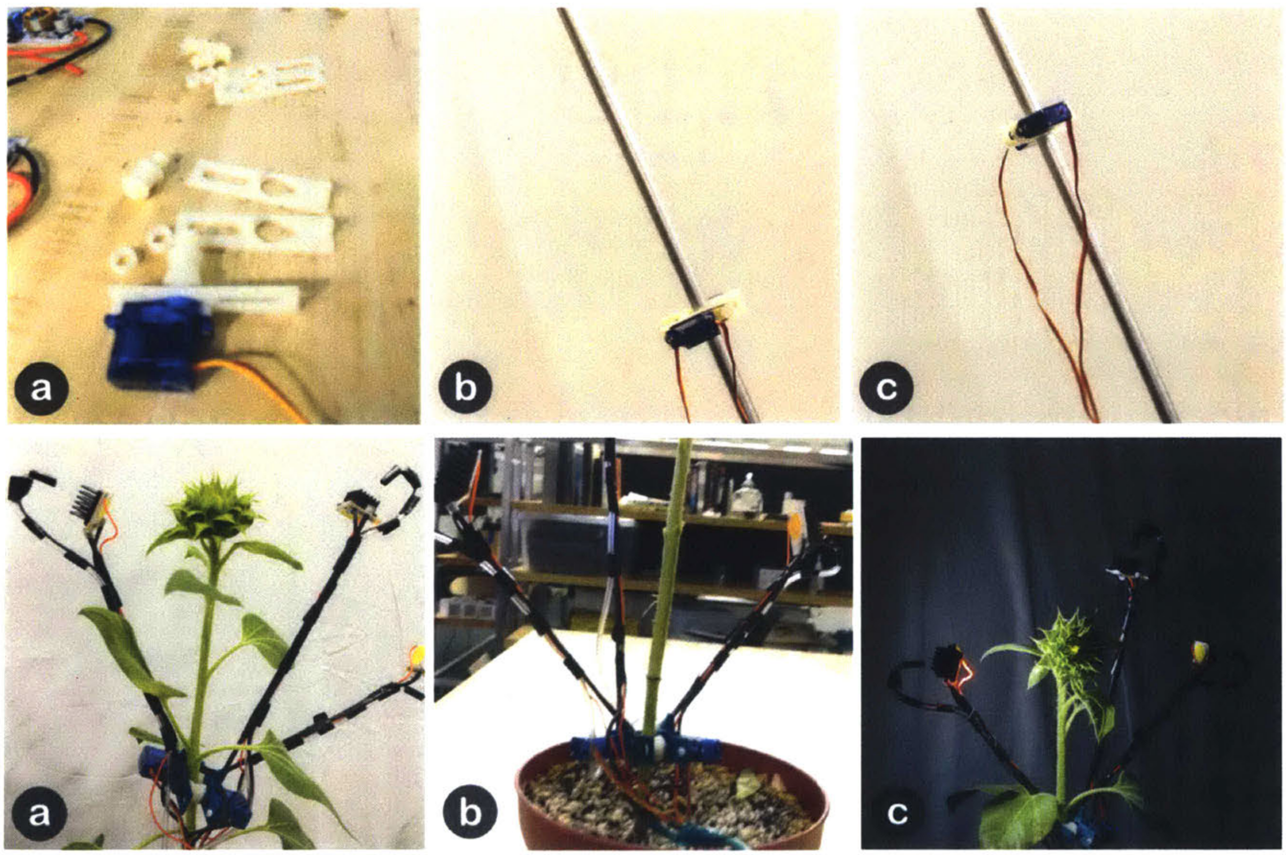


Figure 8.9 Top Row: a) 3D printed parts for the plant climbing robot, b) and c) show climbing and surface tolerance test on an Aluminum rod (substituted for test before a plant stem). Bottom Row: a)-c) Design I of the plant climber robot on the stem of a sunflower. c) shows one of the light switched on and providing energy for growth to the plant

### 8.4.5 Locomotion

The locomotion implementation is consistent in all the variants of the design. The stem thickness is assumed to be 0.75cm or greater. A parabolic shape of the wheel aids in more contact area with the stem. The robot parts were printed on Dimension (Stratasys 1200ES) since the finish led to less friction for locomotion and allowed the robot to tread on irregular surfaces easily. The wheels are allowed to move in only one plane with an orthodontic elastic on either side maintaining its tight contact with the stem. The design is self-regulatory and was observed to perform well even on rough surfaces with one wheel compensating through elastic for the other.
The 3D printed wheels are covered with foam tape for a soft yielding characteristic and finally covered with self-fusing silicone tape. This prevents the robot from rupturing any stem tissues when in motion.

### 8.4.6 Lighting / Spectroscopy

Since the healthy growth of plants was observed in the greenhouse, a spectroscopy and intensity readings were taken to verify the spectrum on the onboard lighting. The greenhouse comparison between greenhouse lighting intensity and spectrum is in the pictures below.

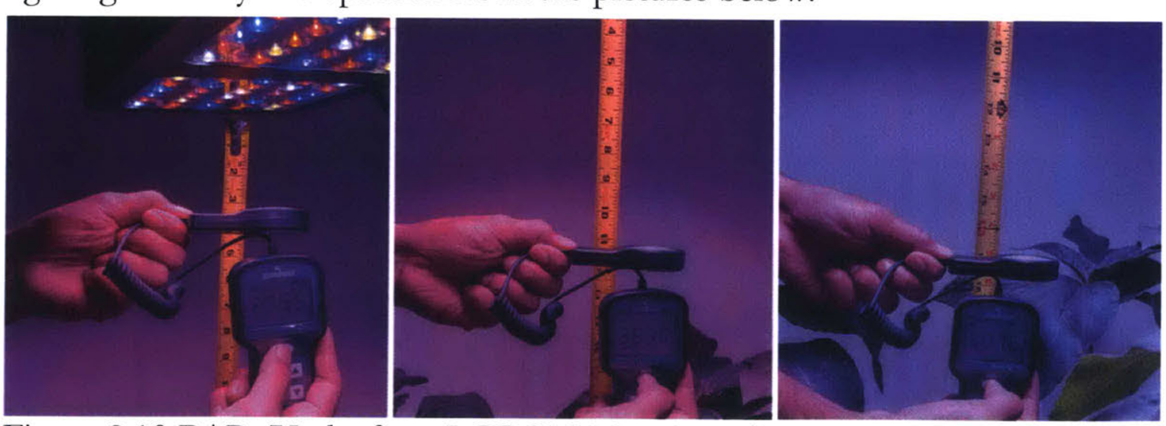

Figure 8.10 PAR (Hydrofarm LGBQM Meter) readings (L to R: 2559, 965.8 507.6 umol $m^2s^{-1}$ at a distance of 3", 11", 17" (at 2" from plant) from the grow light) taken from the greenhouse where ideal growth was observed for plants during early. PAR readings were suggestive for robot's on-board lighting

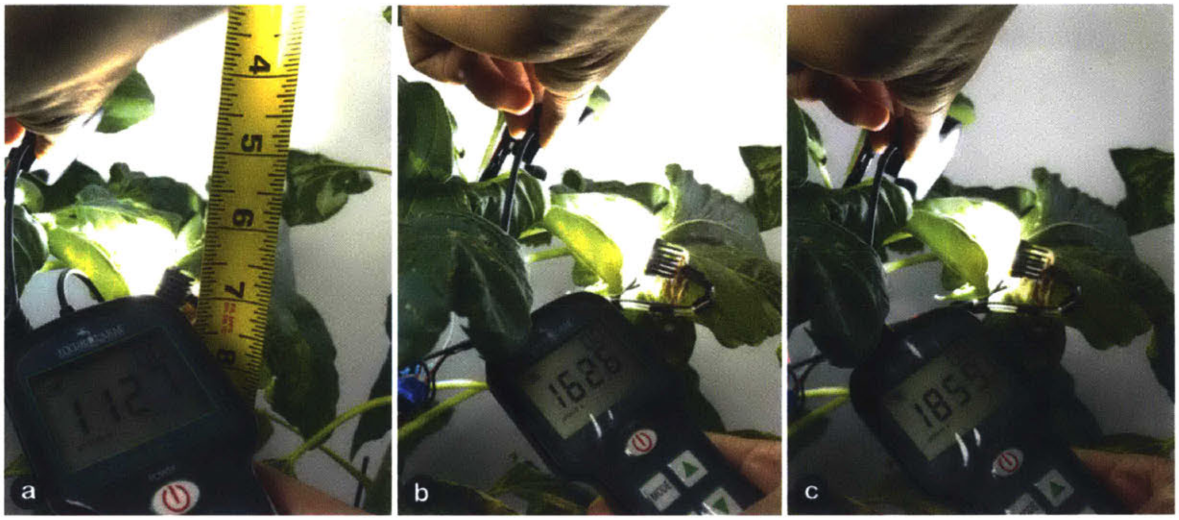


Figure 8.11 PAR Readings from onboard low weight high power LED lighting on the robot. Tip of plant is 6" away (1127 umol m$^2$s$^{-1}$from the light that in on). Probe set 4" and 2" inches from the light shows 1626 and 1858 umol m$^2$s$^{-1}$ respectively.

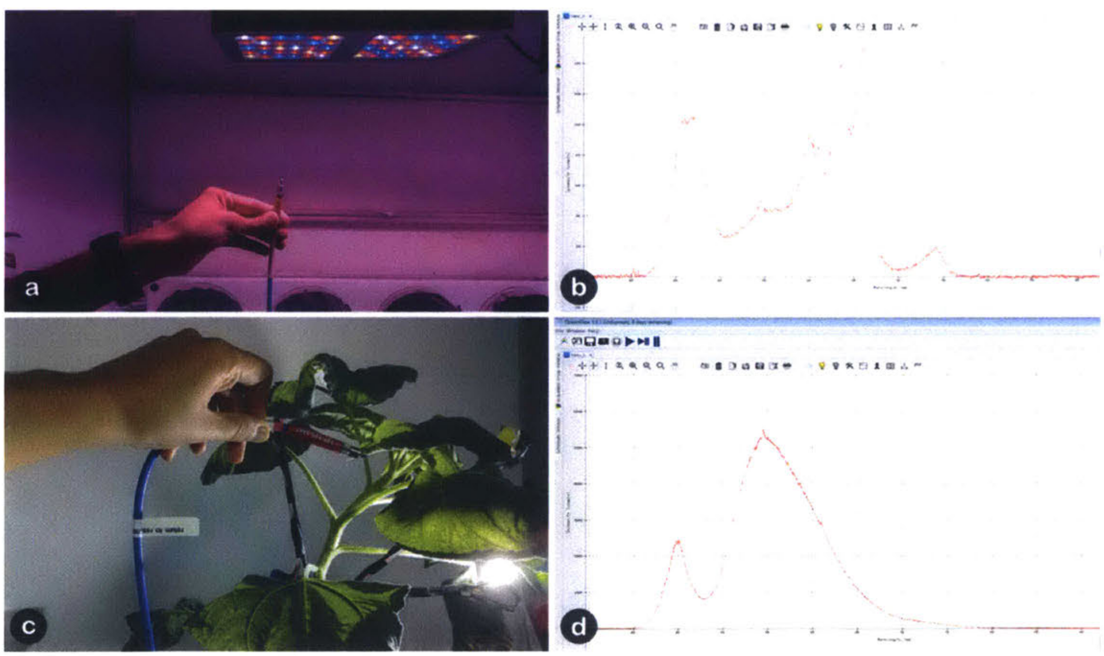


Figure 8.12 Spectroscopic tests to compare ideal grow light and onbaord robot light to ensure optimal growth of the plants and visibl results after 6 weeks. Top: b) shows peaks around 470nm and 720nm (since grow lights don't carry green LEDs). Bottom b) shows a full spectrum observed in the 6500K 25W light onboard the robot. Spectrometer: OceanOptics USB-4000 VIS-NIR

### 8.4.7 Electrical and Software:

Each robot unit has high power LEDs with a common ground (16AWG Stranded Hookup wire) to reduce any wire weight. The positives of the light are connected to SSD Relays (Digikey 255-1568-ND, 2.6A Load current), toggled on/off with an Arduino microcontroller. The Arduino is connected to a Raspberry Pi 3 Model B running an openFrameworks application on local time, sending serial to microcontroller to switch on/off the lights (Turn on/off:5am, 11pm). This helps in maintaining photoperiod for the plants and remote control through RPi for maintenance without manual intervention. For schematics of the relay board, please refer to Appendix B Section B.3.

### 8.4.8 Phototropic Training and Output

Figure 8.13 Batch I (Pro Cut Gold F1) Sunflower 6 week phototropic robot trained output.

The following pictures show the output and events during directed growth of of Russian Mammoth plants.


Figure 8.14 Automatic plant shaping with phototropic robot. a) Robots mounted on the plants on 06/14, b) Shaped plant output after 32 days (4.5 weeks)

Initially, these plants were grown in the greenhouse until they had straight robust stems. Subsequently, a 4.5 week growth plan (Figure 8.15) was scheduled with an objective of final shapes for each. This growth was powered with phototropic robot's high power LEDs. Fig 8.16 shows curving behavior of the plant towards robot mounted light over a period of 7 days. Expanded sequence of the same is shown in Fig 8.17.

Following this, a 32 day sequence of auto-shaping four plants is shown in Fig. 8.18 and Fig 8.19

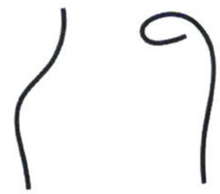

Figure 8.15 Left: Planned growth primitive for Pots 1-3, Right: Spiral for Pot 4

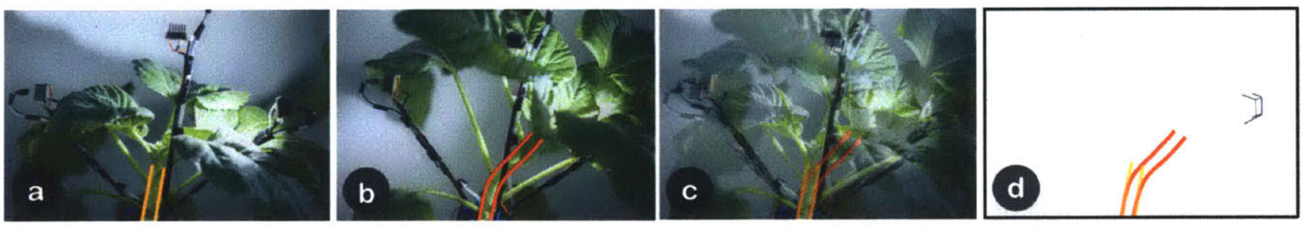


Figure 8.16 a) First picture after the robot moved to a new position and stayed put for 7 days, b) Phototropic behavior of the plant to move towards the light. Lignified growth after 7 days, c) Overlay of first and second pictures to show light following behavior of plant that is the basis of phototropic training in this case, d) Orange: Stem shape on day 1, Red: New growth towards light after 7 days

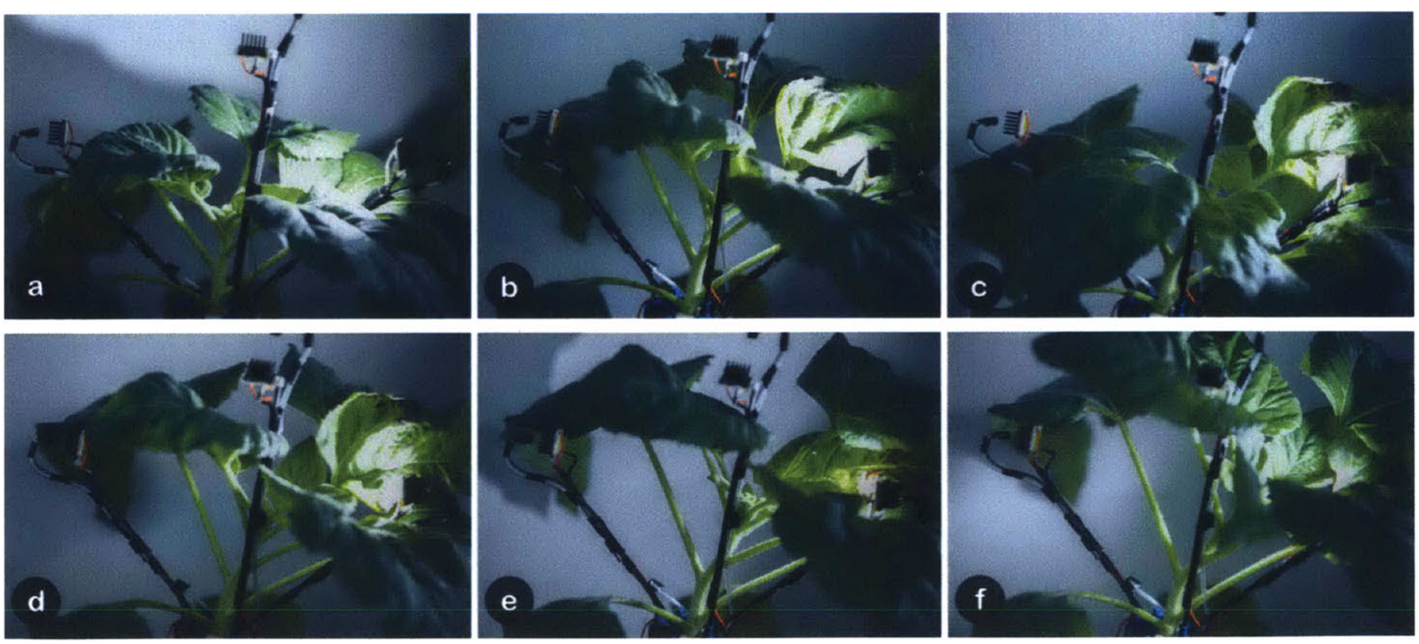


Figure 8.17 Phototropic growth training output shown over a period of 7 days. a) - f). Note that this is lignified growth and not reversible motion as in helioptropic movement of sunflower.

Figure 8.18 Timeline of the first 10 days of growth training. Each picture was taken at beginning of the day (lights-turn-on event). The events go from Left to Right, Top to Bottom respectively. Day 1: 06/20, Event 10: 06/29

Figure 8.19 Timeline of the the last 10 days of growth training. Each picture was taken at beginning of the day (lights-turn-on event). The events go from Left to Right, Top to Bottom respectively. Day 1: 07/04, Day 10: 07/13

Pictures 1-6 in Fig 8.18 show straight stems being curved to follow the light. Pots 1-3 have plants curving towards right whereas plant in Pot 4 curves left. It was observed that the plants took an average of a week to lignify growth. The robot was thus stationary for one growth event for these days before moving up automatically on the stem by 0.75"-1" inch per week.

Figure 8.20 Overlay of planned with observed growth. Grey shows unfinished growth when the picture was taken. Refer to 8.18 Picture 1 for the starting growth reference.

Phototropism is the natural response of a plant towards light. As a result, training with the phototropic robot was observed to have precise control over growth trajectories as shown in Figure 8.20. Through this experiment, I conclude that training through the proposed phototropic robot can be a successful approach of directing the growth without stressing a plant. Future research would focus on outdoor training of plants and observation of directed growth by averaging natural and artificial light sources. In addition, a self-sufficient powered system (such as solar powered robot) would pave a way to independent long term in-field deployment.

## 8.5 Future

### 8.5.1 Plant shaping through Gravitropism

In another trial of plant shaping, I implemented a Gravitropism-based plant shaping rig inside the greenhouse. The planters are mounted horizontally on stepper motor controlled rotational platforms.

The rotation of steppers is coupled to lazy susan rotation mechanisms to reduce load of stepper shafts. The program rotates the plants every 5 days in different direction to program spiral, square or other growths. At the time of implementation, the specimen didn't get to vegetative growing stage and only preliminary results were recorded.

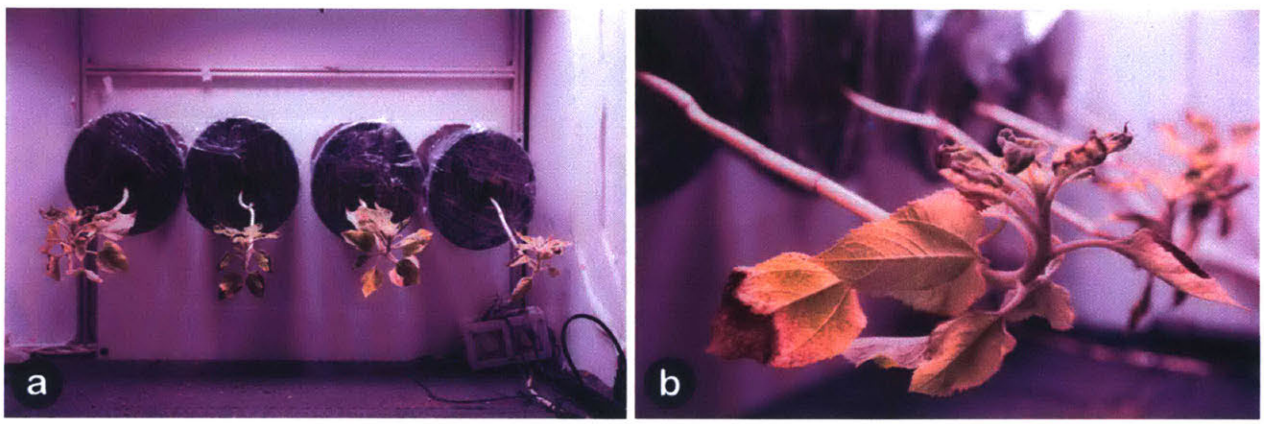


Figure 8.21 Gravitropism based plant growth training rig. Plants grow opposite to gravity and a computer program rotates the pots every few days to program corresponding growth in the plants.

### 8.5.2 Training growth with stress/scaffolding

Principles of symbiotic robot on the plant and using plant-as-scaffold also extend to other mechanisms such as applying stress to shape the plants as done in a few manual practices. For species such as bamboo, this is especially useful and can account for outdoor usage.

# 9. Conclusion & Future Work

*[...] "what I have really said is, that all are not as perfect as they might have been in relation to their their places to intruding foreigners" [...]*
*Darwin, Origin of Species*

Machines in the cybernetic loops of human functions have profoundly reconfigured our composition (Haraway, 2006) externally and internally, rendering us with superior capabilities. Modification of our own selves is already modification of the nature. In this quest, compounding our ecology with machines will align their evolutionary vector with us. This thesis was an effort in direction of such hybridization through use of plants.

I initially showed the analogy between the electrical responses in plants and humans (Chaper 3). Such 'animalness in plants' was my initial motivation of seeing ecology and humans together in the purview of evolution that we are driving. Elowan (Chapter 5) is a plant-machine hybrid, where the plant is in dialogue with technology. The agency rests with the plant and it drives itself towards light with its signals as triggers. Such new symbiotic association with the robot added mobility to the plant.

The non-native functions I design throughout this thesis are purposefully in association with the capabilities that the plants already have. Chapter 6 was a design study of new electronic channels grown inside the plants. With the large scale of plants in the environment and our quest to interact in it, plants are an ideal species to introduce such sensors. Such synthetic electronic channels could also serve for output modalities as outlined in the design space. Circuit design in electronics encompasses circuits with contacts, interconnects, components, elements and more. As we go beyond the state of the art of single conductive channel towards more 'in-planta' components, the design space will correspondingly scale as well. Future research should also address means of deployment and self-sufficiency running with the plant system.

Chapter 7 introduced lead sensors that worked with the water transport mechanism of plants. CNT-functionalized fluorescent dye-labelled dsDNA produces visible readout at 650nm. CNTs reside within the intercellular space in the plants. The plant's water uptake brings in Lead (II) ions which cleave dsDNA and quench visible fluorescence. Such in-vivo turn-off detection works owing to the plant hydraulics and can be deployed in industrial towns to monitor various environmental parameters. The current limitations of the sensors are bleaching when constantly exposed to visible light. In addition, mechanisms of deployment when not using water culture need to be further researched. However, such sensors are a promising method for agriculture, environmental monitoring and so on.

Characterization of nanomaterials such as carbon nanotubes has shown to be possible in the terahertz or microwave domain. In-vivo characterization of nanotubes in plants could pave a way of long distance monitoring and data gathering multiple plants in a field with single towers. Nanomaterials could also act as effectors with an element release triggered through electromagnetic waves. Such research altogether would be a step in building a bidirectional digital to biology bridge; integrating our ecology with the digital systems.

Chapter 8 highlighted the morphogenetic plasticity of plants and their growth responses to the environment. Architects and synthetic biologist have together dreamt of a world where the growth program could be encoded in the cells to be able to grow houses that integrated within in our ecology. Along these lines of thought, a new symbiotic association was crafted with a climbing robot living on a sunflower plant. While the robot used the plant as its scaffolding, it also trained the plant's growth using onboard lighting. Two batches of Perennial sunflowers were grown for this test for 6 weeks each with the growth and output recorded. Successful results were shown with the final plants robotically shaped. Other means of auto shaping were also explored such as Robotic Gravitropism. In the future, such growth training will be done on a longer timeline with Timber Bamboo for architecture and furniture objects. Different mechanisms of plant training such as stress based shaping will be used in such cases. A successful execution could enable greenhouses to not only grow crops but perhaps furniture one day. I envision a plethora of such shaping robots being left in a forest and shaping architectural frameworks and objects over time.

Finally, this thesis has an overlap with several disciplines: plant biology, biotechnology, electronics, robotics and more. The ideas and the research I presented were a personal ambition towards using nature for design, interfaces and interaction. In this process, I peeked at a few capabilities of plants to create symbiotic associations with the artificial world. However, an Augmented Nature, as a part of our design process is only the beginning. The merger of plants and machines will allow us to realize capabilities that we could never achieve in the silicon world alone.

# Appendix A

Figure A.1 Mammoth Sunflower (Batch II) planting: 06/07/17.
Specimens for auto-shaping using phototropic robot

Figure A.2 Mammoth Sunflower (Batch II) planting: 06/22/17
Specimens for auto-shaping using phototropic robot

Figure A.3 ProCut Gold F1 (Batch II) sunflowers 04/30/17
Shorter final length than Batch I

Figure A.4 All plant species that were later augmented. Left half: Rosa Floribunda, Right Half Top: Venus Flytraps and Arabidopsis, Right Half Bottom: Homalomena, Daisies for plant hybrid robot

# Appendix B

Phytoactuators Schematic

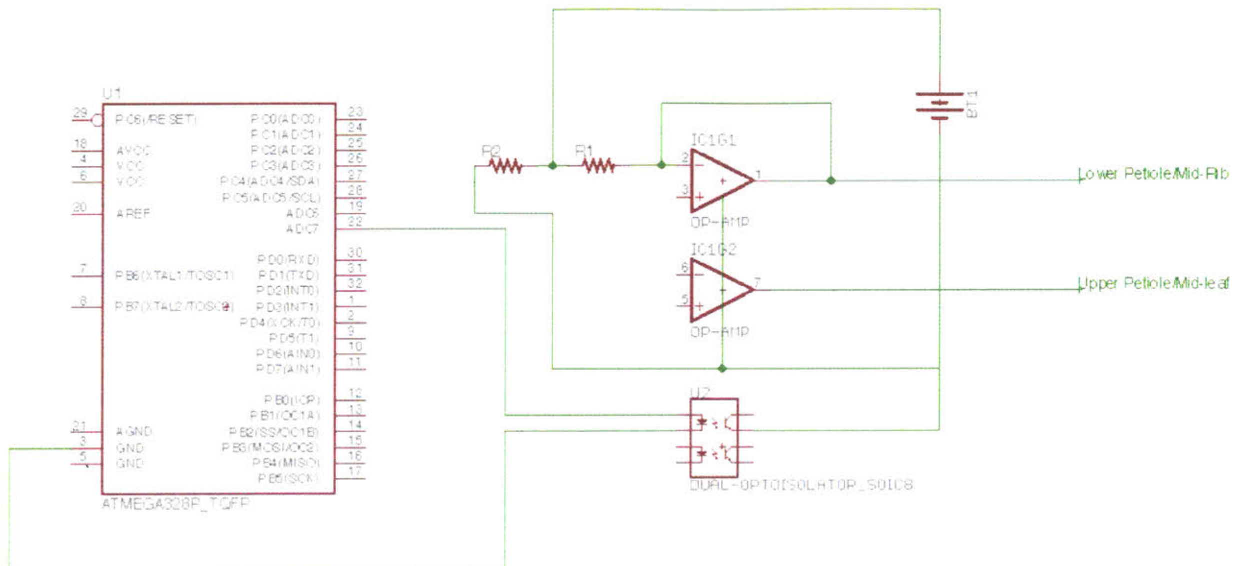


Figure B.1 Actuation Trigger circuit for Mimosa Pudica and Venus Flytrap leaves. The microcontroller receives serial from openFrameowrks application to trigger voltage difference across the plant organelles

Schematic of Plant Signal Amplification for Elowan – Plant Robot Hybrid

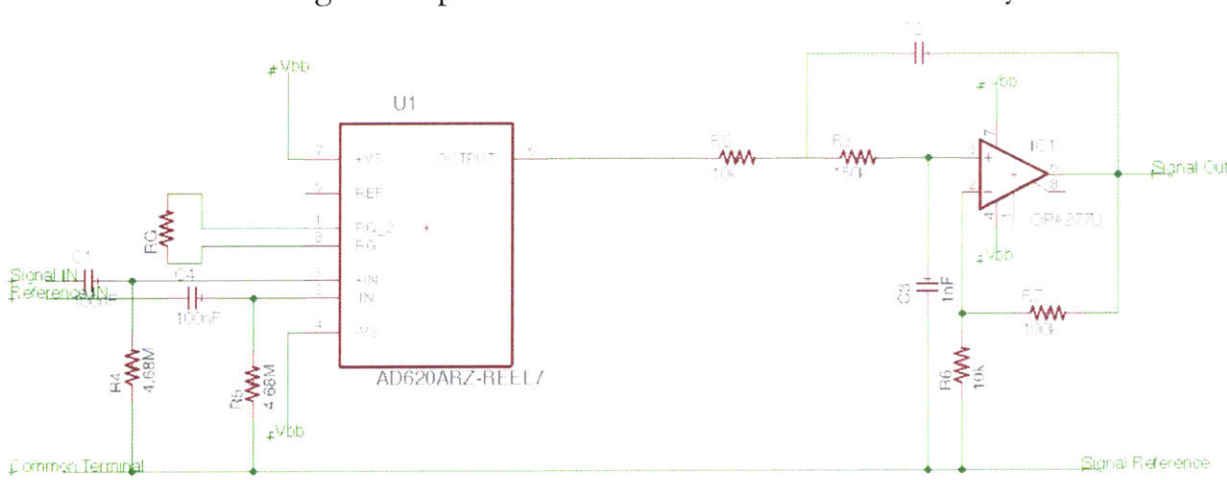


Figure B.2 This circuit amplifies the electrical potentials inside the plants. The input potentials from two differnet leaves and then fed into the robot circuit to trigger movement towards either side

Eagle schematic of the relay board for light switching of phototropic robot
This goes into the header pins A0-A8 Arduino Uno like a mini shield.

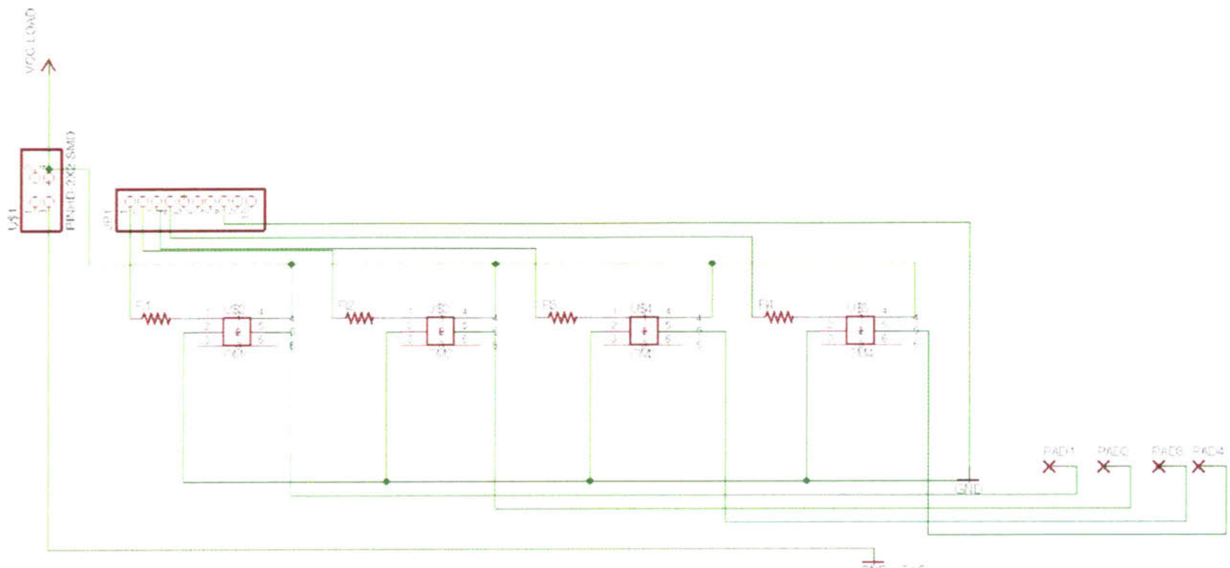

Figure B.3 Eagle schematic for Arduino Relay board mini shield that toggles high-power LEDs on-off

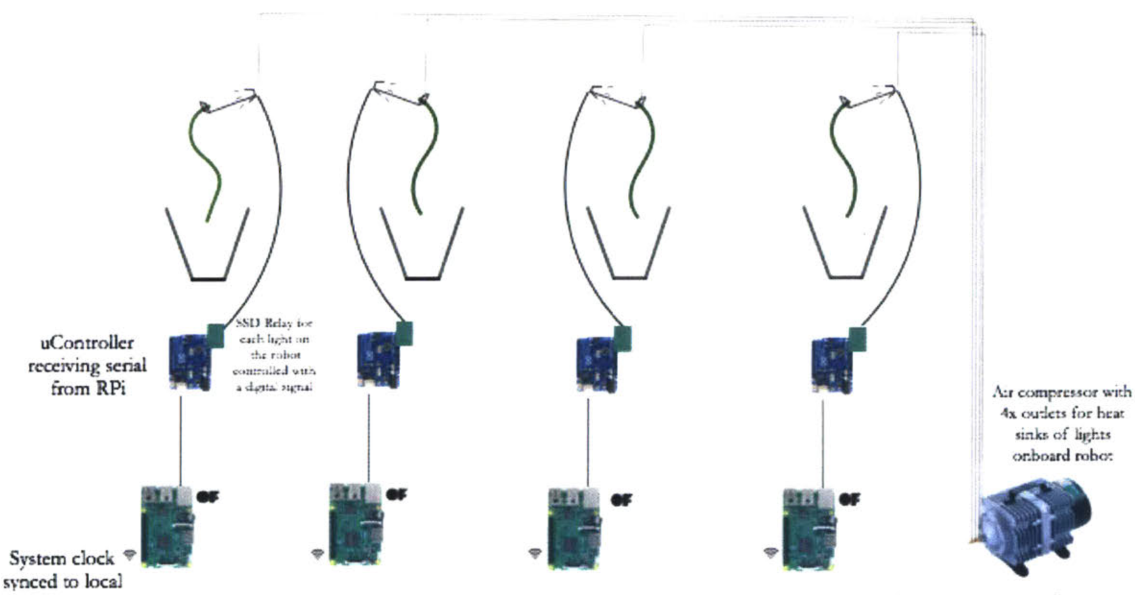


Figure B.4 Plant shaping setup for 4 plants. Local clock synced serial sender application digitally switches on/off relays for robot lights. A power relay controlled through RPi turns an air compressor on/off as per the light on/off schedule

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