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Expressive Phyto-Extensions
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EXPRESSIVE PHYTO-EXTENSIONS

*Design and Engineering of Plant Wearables for
Communicating Environmental Information*



A thirty-six-unit thesis submitted to Carnegie Mellon University
in partial fulfillment of the requirements for the degree of
Master of Science in Computational Design

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Contents

Acknowledgement.....	2
Contents.....	3
Abstract.....	5
1.Introduction.....	6
1.0 Motivation	7
1.1 Thesis Overview	7
2. Background	8
2.0 Human-Nature Relationship	9
2.1 Human-Plant Interaction.....	12
2.2 Critiquing	17
3. Expressive Phyto-Extensions.....	21
3.0 Why extensions? What do they do?.....	22
3.1 Why tangible interface?	25
3.1 Material and Interface Selection.....	29
3.2 Prototypes	30
Inter-species Communication (see Figure 13)	30
Protecting / Sheltering (see Figure 14).....	31
Assisting Horticulture/Agriculture (see Figure 15).....	33
4. Design Workflow.....	34
4.0 Design Challenges.....	35

More-than-human-centered Approach.....	35
Sustainability.....	37
4.1 Workflow	39
Context-driven Design	39
Expression Dictionary.....	42
Workflow Example	52
5. Fabrication.....	53
Principal Mechanism	54
Software	54
Hardware and Heat-sealing Process.....	57
6. Discussion and Future Work	59
6.0 Limitations of current prototypes	60
6.1 Application Context.....	60
6.2 Future Work.....	63
Integration of Artificial Information Processing	63
Alternative Actuation Mechanism and Materials	64
Cyborgian EPEs.....	65
7. Conclusion	67
Appendix A: Interview Transcripts	69
Appendix B: Prototype Evaluation	73
Appendix C: Digital Modelling Workflow	77
References	78

Abstract

Human-nature relationship has gained rising attention in recent decades. There has been an ongoing perception shift on how humans interact with their environments. Unsustainable interventions have not been able to benefit our own species in the long run. Rather, the dearth of knowledge of how the eco-system and the environment operates has increasingly and accumulatively put us into conundrums. Existing efforts that aim for a departure from anthropocentric perceptions get challenged by issues such as lacking first-hand experience from non-human entities, limited understandings of their urges and needs, etc. This thesis acknowledges those challenges and continues the effort to help humankind be better informed of the ecological and environmental stresses in their surroundings through a more-than-human approach.

In this thesis, I present 1) three prototypes whose design and engineering are centered around plants. The prototypes help the plant subjects to actively response to the environment and relay plant-detectable information to humans and animals. 2) a workflow that pertains to alleviate some of the difficulties when designing for non-human entities through context research and rapid prototyping. 3) a fabrication process that enables people from various backgrounds to be able to rapidly prototype with inflatable shape-changing interfaces. Expressive Phyto-Extensions, in near future, are anticipated to be integrated into a both biologically and computationally mediated system that can wholistically achieve the design visions discussed by this thesis.

1.Introduction

Current technologies have made it possible for natural systems that used to be considered as operating at the scale of years, seasons, and days to be capable of giving instantaneous and dynamic feedback. Computational systems translate information from natural systems into digital representations and make them readable to human beings, which enables us to sense and respond to our environment in a real-time fashion. We can monitor the soil humidity level and nutrient deficiency from our phone app. We can control watering system remotely. We can track the ripeness of the fruit and know when and where to go and forage them with in neighborhoods without stepping outside. Our built environment now is understood as a synthetic expression of direct and indirect human interventions upon ecological systems and their processes. The evolvement of the ecological environment is no longer separable from humans' interactions with it. How we design our constructed world impacts how we interact with the natural ones.

1.0 Motivation

The pandemic has drastically changed the way how people think about nature and their living environment. More and more people desire to spend more time with nature and be part of it. The therapeutic and restorative effects that nature has on people is long known. The lockdowns as accelerators make people more aware of the preciousness of clean air, free walks, and open space. Gardens that support biodiversity, provide interactions, and grow food become great assets during the time when food supply was short, and interactions was banned. Interacting with nature is an effective way to help people release stresses and keep sanity. However, a lot of existing technologies whose original intentions were to assist and promote the interactions between humans and plants work in a very oddly opposite way. Instead of encouraging people to spend more time with nature, they successfully kept people away from nature due to the much intelligence they have and much convenience they brought by. Thus, this thesis calls for designing interfaces that truly contextualizes the interaction between humans and nature through site-specific exposure and perceivability.

1.1 Thesis Overview

Chapter Two presents a context that covers human-nature relationship and human-plant-interaction precedents to reveal the design motivation and design space of Expressive Phyto-Extensions.

Chapter Three defines Expressive Phyto-Extensions: what they do, what their significance is as an interface for promoting human-plant interaction and how they relay environmental information. This chapter talks about the choice of a tangible interface over a digital one and the consideration and selection of the materials. In this chapter, three assembled prototypes are presented.

Chapter Four explains the design workflow, providing a framework that promotes a more-than-human-centered approach and sustainability. The provisional framework can potentially be expanded into a more holistic process that helps designers to design Expressive Phyto-Extensions through various partnerships and collaborations. A dictionary that compiles both functional and fabricable vocabularies that designers can reference when conceiving and implementing assemblies is also provided.

Chapter Five documents the fabrication process of the prototypes, which includes both hardware and software operations.

Chapter Six covers the evaluation of the prototypes, envisioned application context of Expressive Phyto-Extensions and the discussion of limitations and future works.

2. Background

This chapter breaks down mainly into three themes: current issues regarding human-nature relationship, the status quo of human-plant interaction design and the research gaps found through literature review. The first theme plays an important role in contextualizing the research question. It introduces why plants matters and why humans should care. The second theme takes a thorough and closer look at the state-of-the-art approaches in fields. The third theme zooms into the gaps and challenges this thesis tries to fill and overcome. Those three themes are inseparable and interdependent. They together guide the subject matter of my thesis.

2.0 Human-Nature Relationship

Interaction with nature has been known for being therapeutic, recreational, and rehabilitating for people. Well known theories of the restorative influence nature has on humans include the Attention Restoration Theory of Kaplan and Kaplan (Kaplan 1995) and the psycho-evolutionary model by Ulrich (Ulrich et al. 1991). Nature gives people an opportunity to be away from routine activities and thoughts. It attracts involuntary attention that requires no effort. It also gives people the idea that you are in a whole other world that has a meaning and is well-ordered. It was also suggested that nature has patterns that reduce arousal, and therefore, reduce our feelings of stress, especially in a modern world, where we are constantly bombarded with so much noise, movement, and visual complexity (Elings 2006).

The burgeoning of technology has rapidly made cities hubs of information and data. Despite the much convenience brought to us by cities and their infrastructures, the trend of having a lifestyle that is closer with nature has become prevalent in recent years, especially under a pandemic setting. “For many people, functioning in the natural setting seems to require less effort than functioning in more ‘civilized’ settings, even though they have much greater familiarity with the latter” (Kaplan 1995) As Stephen Kaplan mentioned in his journal paper ,



Figure 1 Vlogger Ziqi Li, Source: Youtube, 17 million Youtube subscribers; 2.2 billion Youtube Channel Views.



Figure 2 Pickup Limes, Source: Instagram, A Youtube community of 3 million friends

“It is as if there were a special resonance between the natural setting and human inclinations.” (Kaplan 1995) These inherent connections between humans and nature explained the phenomenon that online influencers such as Ziqi Li (see Figure 1), Pickup Limes (see Figure 2), who advocate lifestyles as such attract millions of followers around the world. These might be meaningful phenomena to examine and there could be important implications in terms of basic human needs. Take Ziqi Li’s success as an example. Other than many factors behind her success, one of the reasons that made her videos go viral is that she presents an almost anti-industrial lifestyle away from our daily “modern” life that shows her audience an exit to be away from pressure, stress, and mental fatigue. Many of her videos unfold the process of how one lives with natural patterns, indigenous materials, and conventional wisdom. Although the images from screens cannot provide us access to the direct benefits we can otherwise get from the exposure to real nature, they nevertheless

become supportive of the inclinations of those who seek a respite from their urban life just by providing this vision and showcasing the possibility.

“You might have walked into the mountains and, after a few hours, felt clearer, more alive, vividly aware of what matters to you and what is just distraction and time-wasting; or you might have woken up on a farm and felt intensely the nearness of living things, the ways that plants, animals, and soil are linked in growth, eating, and decay.”

--- Jeddediah Purdy, *After Nature*

Although “soft fascinations” (Kaplan 1995) found in natural environment already help enhance human’s well-being by readily holding people’s attention in an undramatic fashion and leaving people plenty room to think about other things, active human involvement with nature is believed to be the way for maximizing the therapeutic benefits of nature. Holding onto this belief, a lot of interactions with nature are designed for clinical and healing purposes. The benefits are later both qualitatively and quantitatively verified through psychological, cognitive, and sociological experiments and research. Groups of people with Alzheimer, learning disabilities and schizophrenic, to name just a few, can benefit from healing gardens. Communities enhance their cohesion among the residents through shared gardens. Other positive benefits of active participation in interacting with nature include, but not limited to, social integration, increase of self-confidence, self-esteem, and concentration, and learning of practical skills, structure, and routine. (Elings 2006)

Despite all the known benefits of nature to humans, there has been little research into the changing role that nature plays in urban space. (Smith, Bardzell, and Bardzell 2017) Understanding how natural lives adapt to the built environment, how they are interwoven to existing urban fabric and what human intervention means to our ecological system are essential if we were to envision a hybrid future of cohabitation. Suzanne Simard in her book *Finding the Mother Tree* (Simard 2021) described that she noticed, when working in the logging industry, that the trees that were planted in grids looked awful, which goes against people’s belief that they could grow more wood than occurred naturally by planting trees in grids and filling all the gaps. She asked, “Why, in contrast, did the wild ferns germinating in that old-growth patch look so brilliant?” In the experimental project *The Social Lives of Urban Trees* (Strickland 2017), Rachel Strickland revealed to us that urban street trees have never been ‘happy’ since day one when they were introduced to the cities to help reduce urban pollutions hundred years ago. Urban street trees don’t have a supporting eco-community as that of forest trees and the disconnection to a supporting system leads to all sorts of health issues in urban plantations.

Moreover, human activities have been the dominant detectable influence on the inhabitability of Planet Earth. Resulting from human interference with natural flows of energy comes climate change, land surface change, sea level change, etc. Altogether, they grow

into a Frankenstein's monster that can become overwhelmingly large and eventually devour our species with ease. "Carbon dioxide has increase 31% since preindustrial times, from 280 parts per million by volume (ppmv) to more than 370 ppmv today, and half of the increase has been since 1965." "City climates differ from those in surrounding rural green areas, because of the 'concrete jungle' and its effects on heat retention, runoff, and pollution, resulting in urban heat islands." (Karl and Trenberth 2003)

Maintaining the health of the overall inhabitable environment on our mother earth is to promise the survival of our own species. In a post-natural era, re-examining the definition of symbiosis, cohabitation requires us to reconsider our relationship with nature, our fundamental needs and desire and most importantly, the impact of all those.

Current sensing technologies have already enabled us to understand our environment in an almost real-time fashion. We are better equipped daily with advancing technologies to understand local and global environmental challenges that we are facing in our physical world. Although sensors could contain a much broader definition, most of our current sensing technologies are yet still electronic instantiations. Scientists, engineers, designers have been constantly studying and referencing nature while designing artificial products. And yet, living organisms still outperform most of human engineering not only in their efficiency and diversity of functions but also in their renewability. When we extract environmental information from living organisms of other species, we are leveraging the smartest sensors ever and learning tricks from nature. Arthur C. Clarke once said in *Profiles of the Future: An Inquiry into the Limits of the Possible*, "Any sufficiently advanced technology is indistinguishable from magic." In this thesis, I would like to quote and rephrase this saying,

"Any sufficiently advanced technology is indistinguishable from nature."

Nurturing natural sensors is not something new. As early as in 2011, Stacey Kuznetsov, et al, proposed this idea of "expanding the current landscape of sensing to include living organisms such as plants and animals, along with traditional tools and digital devices." One of the opportunities they saw for ubiquitous computing is to incorporate traditional technologies and living systems into ubiquitous sensing applications. (Kuznetsov et al. 2011) In their research, they studied "practices of gardeners, beekeepers, zoologists and other 'experts' in the domain of organic and non-digital sensing". Here is a list (see Table 1) of behavioral key words used for describing participants' practices and a list of tools used for interacting with living organisms and evaluating the environment in the research.

Behavioral Description	Tools
Routinely	ORP sensors
Motivation / enjoyment	PH meter
Skill	Spectrophotometer
Active noticing	Dissolved Oxygen Meter
Expert knowledge	Refractometer
Experiential	

Table 1 Behavioral Descriptions and Tools used in Nursing Natural Sensors

It is not hard to conclude that in order to incorporate living organisms as natural sensor for us to better understand our environment and take better actions related to protecting and improving our ecosystems, it requires a specific group of people with expert knowledge and a huge investment of their time as of today, as well as special equipment for assistance in the process. Following the proposal by Stacey Kuznetsov, et al, of how to explore approaches for leveraging living organisms, traditional tools, and digital devices to shift the current sensing paradigms, in this thesis, I look at the design and engineering of the interfaces between plants and humans as part of the hybrid infrastructure to help us to better interact with nature, supporting biodiversity and preserving the richness of our ecosystem.

2.1 Human-Plant Interaction

Among all the non-human living organism species, plants may count to 5% of them in total. (Mora et al. 2011) Unlike humans and animals, plants don't have brains or neuronal networks. However, they have embedded distributed biological computational systems to help them cope with complex and challenging environments. (Duran-Nebreda and Bassel 2019) Although often seemingly inconspicuous and passive to humans, plants are acquiring, storing, processing, and acting on information that surrounds them. (Mitchell 2011) In fact, plants have as many as twenty different senses, including five of which are also employed by human beings. For example, they can detect electromagnetic force, which is usually undetectable to animals and humans. They can also grow towards light, which phenomena is called phototropism. (Mancuso and Viola 2015)

The very initial proposal of the concept "human-plant interaction" could be traced back to as early as the year of 2007. Kuribayashi, et al, investigated into a tool kit that was designed to "support designers who develop a dynamic interactive system using plants' ecosystems" and they call the design as "human-plant interactions". (Kuribayashi, Sakamoto, and Tanaka 2007). Ever since, people from computer science, design, biology, and art have continued to study the interactions between plants and humans, looking into how to leverage plants as sensors, interfaces, and materials. In the paper *Patterns and Opportunities for the Design of Human Plant Interaction*, I, together with the other authors, systematically reviewed and analyzed "existing Human-Plant Interaction works by presenting a survey of projects across HCI, art/design, architecture, and bioengineering". We screened through 901 records and ended up with 71 papers for close examination and in-depth reading. Five different dimensions are identified as frameworks from core design paradigms, which include HPI System Architecture, Plant I/O Coupling, Plant Interfacing and Manipulating Techniques, Application Context and Scale. (Chang et al. 2022)

In this thesis, I mainly examine research and design projects that leverage plants as sensors with or without assistance of artificial sensing system. Furthermore, instead of focusing on the sensing system, I concentrate on the post-sensing phase – how the output is delivered to

users, what kind of interfaces are designed and used, and how the users interact with them. I leverage the HPI System Architecture proposed in *Patterns and Opportunities for the Design of Human Plant Interaction* as a categoric framework for comparing and analyzing output interfaces in different HPI design configurations. In the paper, HPI System Architecture is defined as “the ways in which a physical prototype’s construction is rigged to interface between the outside world, the technological system (any non-organic, non-plant components necessary to implement the artifact), and the plant system (the live vegetal subject and its corresponding sensory capabilities)”. Four primary approaches are identified under this framework which include indirect integration, proxy integration, embedded direct integration, and augmented direct integration.(Chang et al. 2022) As aforementioned, the indirect integration category is outside the research interest in this thesis as “no component

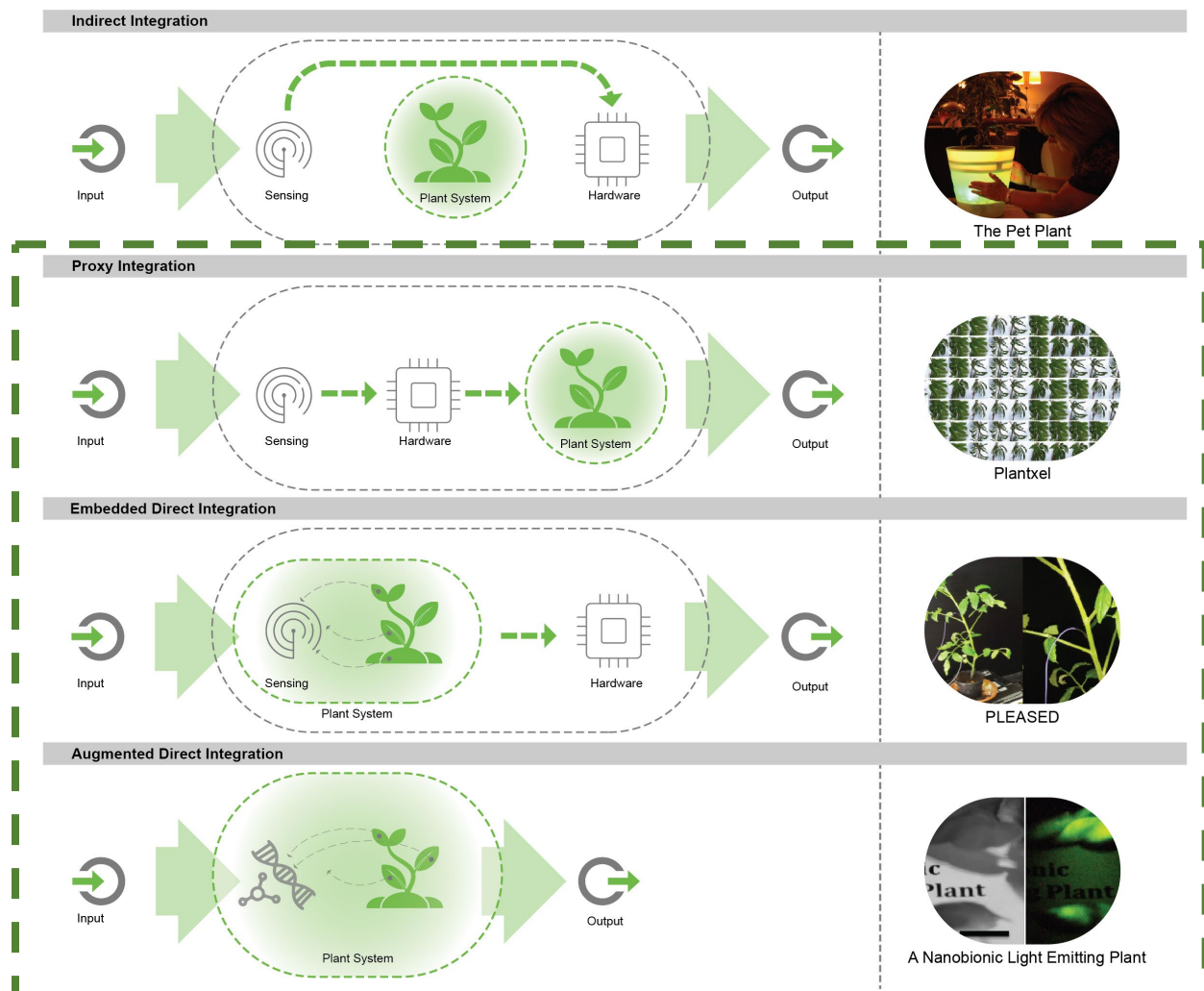


Figure 3 HPI prototype configurations can be generalized into four categories: Indirect Integration, Proxy Integration, Embedded Direct Integration, and Augmented Direct Integration. In this thesis, the latter three categories are referenced. (Chang et al. 2022)

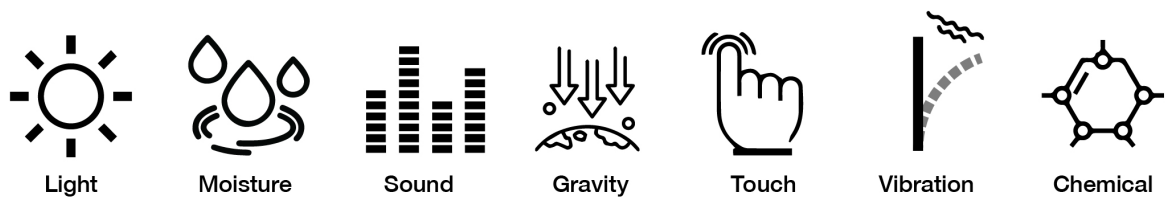
interfaces directly with the plant itself” in the system. Projects that fall under the rest of the three categories are compared and analyzed here (see Figure 3).

Among all the projects that leverage plants as partial or the whole sensing system, the output interfaces could be generally divided into three sorts –plant itself as the interface, artificial devices as the interface, and the combination of the two.

Projects that belong to the Proxy integration category mainly use plants themselves as the interfaces. Those projects leverage either plants’ physiological or morphological changes for displaying information. The information relayed through plants may or may not be plant/environment related. The display through plant itself is a key novel component used to trigger or encourage human interactions. One example is Babbage Cabbage (Fernando et al. 2009), in the control system developed by the team, “visual engagement is accomplished through the relative level of automatically controlled pH values and the resulting changes of color of red cabbage over time.” Different shades are used for indicating real-time environmental information collected from multiple sources. The red cabbages as material themselves hold not only functional but also symbolic significance when tightly coupled with environmentally related information. Another example is Plantxel (Gentile et al. 2018), it is “a conceptual plant-based display with multiple plants as pixels that close their leaves based on external stimuli.” Mimosa is used in this display installation due to its natural mechanism of fast response to stimuli such as touch, air flows, vibrations, etc. This display was intended to convey information in public space in an unconventional way. Unlike traditional plant-based displays, by utilizing the thigmonastic feature of mimosa, it pursues a more dynamic display that involves motions, shades, and different time scales. Similar to Babbage Cabbage, the interface in Plantxel is made of plants themselves and users interact with the plants mainly through visual engagement. Mossxels (Kimura and Kakehi 2014) is a different project with highly-aligned concept. Instead of using mimosa, they used blocks of moss for creating different shades by playing with humidity level. A slightly different example under Proxy integration category is Botanicus Interacticus (Poupyrev et al. 2012), “it is a technology for designing highly expressive interactive plants.” According to this vision, Swept Frequency Capacitive Sensing technology, together with machine learning techniques, were adopted to recognize and estimate the location of human touch along the plants. A wire in the soil was used to connect the plant, the user, and the output platform. The outputs from the plants are eventually captured and translated into visual and audio forms, whose complexity increases with the amount of interaction between the user and the plant. From the demonstration illustrated in the paper, commercially available electronic screens are used as the output platforms. The frequency and intensity of human-plant interaction was translated into digital information and displayed on the screens. Another project that was discussed within this category is Biogotchi (Chien et al. 2015). In this project, by manipulating the light source, the researchers tried to direct the developmental changes of sweet pea vines and train them to map personal information and provoke stronger emotional response. Similarly, in Infotropism (Holstius et al. 2004), the designers used light sources to direct the physiological development of a group of plants to make the users be aware of the impact of their choice.

The group of the plants have a symbolic meaning that represents living organism on the earth, and further implies the health of the entire ecosystem. The directional growth of the plants is designed for encouraging people to recycle more by visualizing the impact of their recycling. In *Patterns and Opportunities for the Design of Human Plant Interaction*, we concluded some of the potential biological outputs that could be leveraged to signal or communicate changes in environment through plants' physiological or morphological properties as show in figure 4. However, the success of such organic display is tightly

Inputs



Outputs



Figure 4 Plant I/O Coupling (Chang et al. 2022)

associated with how much the users know about each plant's development and the degree of control they have over its environment (Chien et al. 2015). A slightly different example that falls into this category is Project Florence (Steiner et al. 2017), although the user inputs also affect the physiological development of the plant by varying its environment, instead of having users directly observe the developmental changes, the output was delivered in a real-time fashion through a text note from a small printer that is integrated with the container where the plant lives in. The concept adopted in Project Florence somewhat overlaps with an earlier project named as PlantDisplay done by Kuribayashi, et al (Kuribayashi and Wakita 2006), in which the team tried to influence the physiological changes of the plants according to the users' mood and communication level. The activity frequencies logged as users' input were translated into environmental stimuli such as light, temperature, etc., that can affect the growth and health of the plants.

For embedded direct Integration, the example discussed within the category, which is the PLEASED project (Manzella et al., n.d.), utilized plants' electrophysiological characteristics and acquire and elaborate the electrical signals by "suitable devices". Plants electrical activities are recorded through placing needle electrodes in the plants. Digital acquisition board is used for taking in the analog signals from the sensors and converts them to digital signals readable by the computers. Thus, computers are the interfaces that users interact with to read the monitored environmental data in this system. One step further, in I/O Plant (Kuribayashi, Sakamoto, and Tanaka 2007), the research team carefully mapped the biopotential variation of the plants relating to environmental stimuli, such as motion, touch, light, etc. Based on that knowledge, they connected plants with electrodes and used plants as part of the control system for controlling external illuminating or acoustic devices. Plantio (Kuribayashi et al., n.d.) is a more focused project led by the same first author using the same conceptual and technical approach as that of I/O Plant. Akousmaflore (Lasserre and Ancxt 2015), on the other hand, translate the variation of biopotentials into different sounds, thus making a plant concert triggered by human touch and proximity.

The direct use of external devices that are attached to or even penetrate through plants in the embedded direct integration system is different from the approach adopted by augmented direct integration category. In this category, "emerging micro-scale technologies like synthetic biology or nanotechnology is harnessed to further enhance plants' abilities to interface with humans and traditional computing technologies". (Chang et al. 2022) Due to the scale of the technology and the molecular level manipulation, the functional materials are typically seamlessly integrated with the plants to give them extra artificial functions. One well-known example is Cyborg Botany (Sareen and Maes 2019). In the project, the researchers seek to "merge synthetic circuitry with plant's own physiology" to "pave a way to make these lifeforms responsive to our interactions and their ubiquitous sustainable deployment". Instead of "deploying external electronics to interface with the plants for inputs or outputs" (Sareen and Maes 2019), they stuck plants into solutions that contain conductive polymers – PEDOT and grew a conductive wire within the plants. This approach was first studied and adopted by the team of Electronic Plants (Stavrinidou et al., n.d.), whose vision was to adopt e-Plants for a wide range of applications, including "precision recording and regulation of physiology, energy harvesting from photosynthesis, and alternatives to genetic modification for plant optimization". In Cyborg Botany, the "augmented" plants were mainly transformed into a living sensor that can detect the proximity and gestures of humans around the plants. One application showcased in the project was the users using different gestures to control a screen through the "wired" plants. In both cases of I/O Plants and Cyborg Botany, external devices are considered as the interface that contains the final output, while plants play an important role as part of the control/ actuating system.

Other plant interfacing technologies that were found in the literature review process such as the ones used in *Vapor-printed polymer electrodes for long-term, on-demand health monitoring* (Kim, Allison, and Andrew 2019), *An in vivo biosensing, biomimetic electrochemical transistor with applications in plant science and precision farming* (Coppedè

et al. 2017), are not included in the discussion as they were mainly for monitoring plants' health purposes and lack the factor of human interaction.

One observation from studying those precedents is that there is quite a bit categorical alignment between the Interaction Modalities (Chang et al. 2022) and HPI system architecture (see Figure 5). It is not hard to notice that most cases within proxy integration category go to indirect interaction, while as the embedded direct integration and augmented direct integration largely fit into the category of direct interaction. This conclusion is essential information for the thesis when deciding on the final approach of designing and engineering of the novel interface that better enhance the interactions between humans and plants.

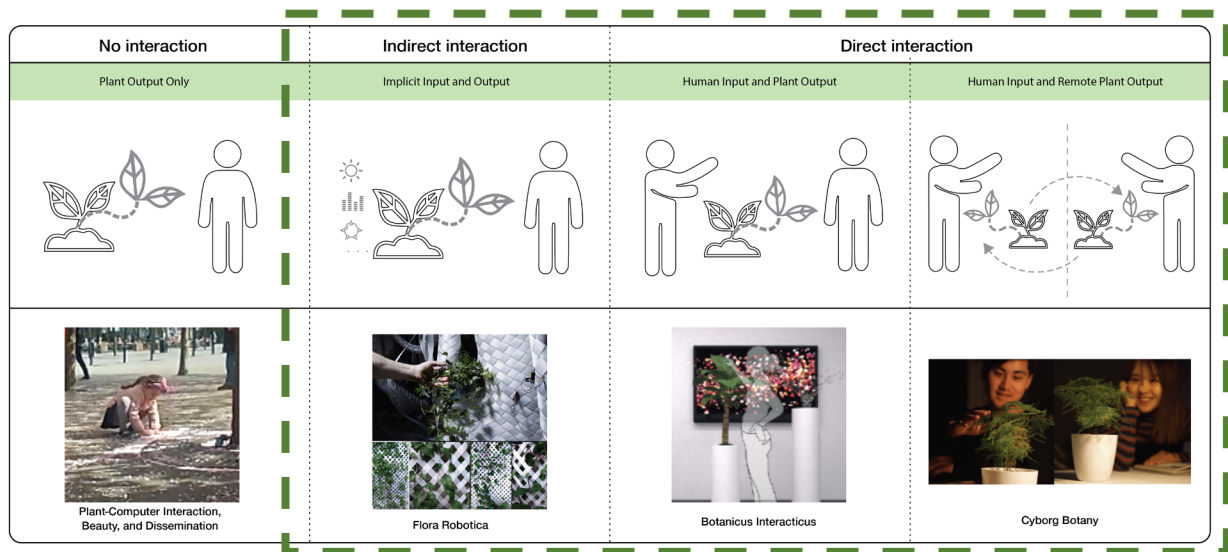


Figure 5 Interaction Modalities (Chang et al. 2022)

2.2 Critiquing

As mentioned in the last chapter, there are three main output interface types can be summarized from the literature review – plant, artificial device, and both. Below is a table (see Table 2) that contains all the precedents discussed in the last chapter to provide an overview of the output interface types of those projects and evaluate their interfaces against five criteria that are considered most important in this thesis for addressing the design vision. This table does not exhaustively compare all the HPI related projects. However, it reveals some of the existing research gaps in HPI precedents that this thesis seeks to fill up. The five criteria that are listed here and is used later in guiding the design and engineering of Expressive Phyto-Extensions is 1) non-invasive, 2) providing plant or environmental health related information, 3) tangibility, 4) outdoor deployment, and 5) information delivery efficiency.

Here is some more detailed elaboration regarding those criteria.

- “Non-invasive” refers to approaches or techniques that do not introduce instruments or other objects or chemicals into the body of plants that could cause possible physiological deformation or vitality damage to the plants. The most widely used invasive sensing method in the example projects is to use electrode needles that stick into the body of plants to get their biopotentials (“PLEASED | PLants Employed As SEnsing Devices” n.d.; Kuribayashi, Sakamoto, and Tanaka 2007; Kuribayashi et al., n.d.; Coppedè et al. 2017). Some less common invasive technologies include immersing plants in chemical solutions that eventually cause the plants to wither or die (Sareen and Maes 2019; Kim, Allison, and Andrew 2019); injecting chemicals that interfere plants biological development (Estévez 2007); mechanically constrain the growth of plants (“Baubotanik: The Botanically Inspired Design System That Creates Living Buildings | ArchDaily” n.d.), etc.
- “Providing plant or environmental health” means whether human users can discern or infer the health status of the plants and their local environment in the interacting process. For this criterion, I have counted the projects that use external stimuli to affect the growth of the plants (Steiner et al. 2017; Kuribayashi et al., n.d.; Kuribayashi and Wakita 2006) and projects that translate environmental information into electronic signals to actuate the system even if the information wasn’t a result of the biological computation of the plants (Fernando et al. 2009) as long as the projects address the issue of plant health or environmental concerns. For projects that use environmental stimuli for mere actuation purposes without caring about health-related or environment-related readings (Gentile et al. 2018; Kimura and Kakehi 2014), they are not considered meeting this criterion.
- “Tangibility” is the criterion used to evaluate the interface that contains the final output of the interaction. This criterion excludes the projects that resort to digital readings as the final format of the outputs, including those that translate the data into more abstract form of visuals or audios yet still keep them mostly on digital screens. It is important to point out that some tangible interactions are designed to happen in the mid of the interacting process, especially those that leverage plants as sensors or transducers. However, since the focus of this thesis is on designing the interface that contains and delivers the output, so “tangibility” here is specifically used to evaluate the final output interface, thus projects such as *Botanicus Interacticus* (Poupyrev et al. 2012) and *Cyborg Botany* (Sareen and Maes 2019) are excluded.
- “Outdoor deployment” is a criterion to evaluate the possibility to have the system being operable in an outdoor environment. For example, in project *Plantio* (Kuribayashi et al., n.d.), one version of the pot is portable, meaning the user can potentially be holding the pot anywhere including outdoor. However, the project still does not meet this criterion because deployment in an outdoor environment was never truly considered in the design process. When deploying a system outdoor, factors such as weather, animals, scale, energy source, etc., need to be carefully examined as it is a much more complex environment compared to that of a lab setting.

- “Information delivery efficiency” refers to whether the output is shown in real-time or over time. For instance, projects that use plants’ physiological or morphological changes (Chien et al. 2015; Kuribayashi and Wakita 2006) for indicating the output information usually have a longer responding time due to the fact it takes time for biological changes to show (to human eyes). Whereas projects that rely on artificial displays (usually electronic displays) can provide a much more immediate feedback (Sareen and Maes 2019; Steiner et al. 2017; Kuribayashi, Sakamoto, and Tanaka 2007).

Project Name	Output Interface	Non-invasive	Plant Health/Environment Related Information	Tangible	Outdoor	Real-time
Babbage Cabbage	Plant	x	x	x		
Plantxel	Plant	x		x		x
Mossxels	Plant	x		x		
Biogotchi	Plant	x		x		
PlantDisplay	Plant	x	x	x		
Infotropism	Plant	x	x	x		
Botanicus Interacticus	Artificial Device	x				x
PLEASED	Artificial Device		x			x
I/O Plant	Artificial Device			x		x
Cyborg Botany	Artificial Device					x
Akousmaflore	Artificial Device	x		x		x
Project Florence	Both	x	x	x		x
Plantio	Both		x	x		x

Table 2 Summary of output interface types in precedents and evaluation against design criteria.

By looking at Table 2, we can tell that no projects that use plants as the output interface adopted invasive technologies. Usually, in those projects, stimuli are placed in proximity around plants to affect their natural morphological or physiological change to convey information visually to human users. The biological computation that happens inside the plants is eventually reflected through the change of their appearance. Those projects rarely seek for immediate feedback. Rather, it is an accumulative process that was designed to reflect the impact of certain stimulus (triggered by human behaviors) over time. Undoubtedly, all the interfaces that are made of living plants are tangible, which differs from digital interfaces. Oppositely, among the projects that used artificial devices as the final output interface, three out of five adopted some sort of invasive technology that penetrates through plants to collect data and signals. In those projects, they mainly leverage plants as living sensors and transducers. Biopotentials that vary within plants as responses to different kinds of external stimuli are collected and then translated to trigger the artificial device with which humans eventually interact. The most frequently used artificial devices in such systems for interfacing humans are digital screens, computers, small-scale electronics, such as lamps, speakers, etc. Systems as such that heavily rely on electronics for both inputs and outputs are able to convey information in a real-time fashion, although only two out of five of them are tangible.

In terms of the type of output information delivered by those systems and designs, about half of the projects have some sort of outputs that are related to either plant health or environmental health including those show in a very indirect way. As mentioned by the team of Babbage Cabbage (Fernando et al. 2009) and Infotropism (Holstius et al. 2004), plants in themselves have symbolic significance when used for providing environmentally associated information. Humans tend to have increased environmental awareness if they can directly see how living organisms respond to their behaviors. Despite the obvious advantage for using living organisms as a means to promote people's environmental awareness in the interaction design, the majority of the precedents only celebrate the novelty of plants as a new interface material that can excite and entertain human users so that they could be more engaged. In this respect, this thesis tries to deviate from an entirely human-centric point of view and touch upon thoughts regarding more-than-human perspective in the design process and how it affects sustainability as a design result, which will be further discussed when defining the functionality of Expressive Phyto-Extensions in Chapter Three.

Lastly, none of the precedents was deployed in an outdoor environment, which is not entirely unexpected when considering those prototypes are products from labs where easier control and fast iterations are advantages. However, when we talk about plants, we think about nature. Nevertheless, none of the precedents has even expressed a vision that their system could one day be connected with and deployed in wild nature. Introducing nature into indoor environment is a great move. But in this thesis, I am concerned with how to design the interaction and what is an appropriate interface that can encourage people to move away from their screens and step out their doors to appreciate our natural surroundings, knowing all the benefits nature has on human beings.

3. Expressive Phyto-Extensions



Expressive Phyto-Extensions (EPEs) are physical interfaces that function as extensions of plants' natural capabilities in sensing environmental changes. Their configurations and motions help plants to actively respond to the environmental and ecological stresses, as well as relay that information, which used to be only detectable by plants, to humans and animals. Expressive Phyto-Extensions are designed and engineered to be part of a both biologically and computationally mediated systems that centers around plants.

3.0 Why extensions? What do they do?

Expressive Phyto-Extensions are hugely inspired by this “cyborgian eco-interaction design” concept proposed by Guyi Yi, et al. (Yi and Di Carlo 2021) The word “cyborg” was first used by Manfred E. Clynes and Nathan S. Kline, both of whom worked at Rockland State Hospital. It was initially defined as organisms with exogenous components that extend the self-regulatory control functions in order to adapt to new environments. (Clynes, n.d.) Came with the word was the context that instead of making the extraterrestrial environments ready for humans, the scientists propose to “alter man’s bodily functions to meet the requirements”.

Artistic projects by Jane Tingley (Tingley 2010) (see Figure 6) and Hannah Brown (Brown 2016) (see Figure 7) are inspirations for migrating the ‘cyborg’ concept from a human-related context to a plant-related one. In the project Branch Replacement, artist Jane Tingley tried to restore the original look of a tree which lost one of its branches in a storm by adding a “prosthetic” branch to the trunk. Within the branch are speakers and sensors that are powered by a combination of solar energy and battery. The project was intended to explore the “unity of nature” and coexistence of human and nature. In the project done by Hannah Brown, the artist used ceramic and rope to create extra branches for a living tree. Those aesthetic components are mechanically attached to the trunk. The alien look of those components triggers a metaphoric exploration of amalgamation of the natural and the artificial.



Figure 1 Branch Replacement by Jane Tingley



Figure 7 Tree Prosthetics by Hannah Brown

Different from prosthetics or orthotics, extensions do not focus on disabilities (see Table 3). Rather, they augment the existing capabilities of living organisms to free them from environmental constraints. Tightly associated with this idea, Expressive Phyto-Extensions are intended to function as an external component that does not interfere the original homeostatic status of plants yet help them to actively respond to environmental stresses and convey the information to humans and animals.

Type	Function
Prosthetics	Replace a (potentially missing) body part
Orthotic	Augments performance of an existing body part
Extension	Extends capabilities with external device
Mobility	Enables movement

Table 3 Types of Robotic Assistance

Building upon this “cyborg” idea and concluding from the gaps found from literature review, I define Expressive Phyto-Extensions as interfaces that exhibit following characteristics and functions:

- Expressive Phyto-Extensions are exogenous components that can be attached and detached to the plants without interfering plants’ biological developments.
- Expressive Phyto-Extensions extend the existing capabilities of the plant subject and relay plant-detectable environmental information to humans and animals.
- Expressive Phyto-Extensions can be situated and actuated in various environments, including outdoor settings.
- Expressive Phyto-Extensions use different configurations and motions as the main pathway for responding and communicating. Other features, such as illuminating, acoustic, olfactory, etc., can also be integrated into EPEs as add-ons.

In I/O Plant project (Kuribayashi, Sakamoto, and Tanaka 2007), the authors had a comprehensive mapping of potential functional roles plants can take on in different system designs where plants’ senses are leveraged (see Figure 8). In their mapping, pattern 2 largely matches what the system architecture designed for this thesis.

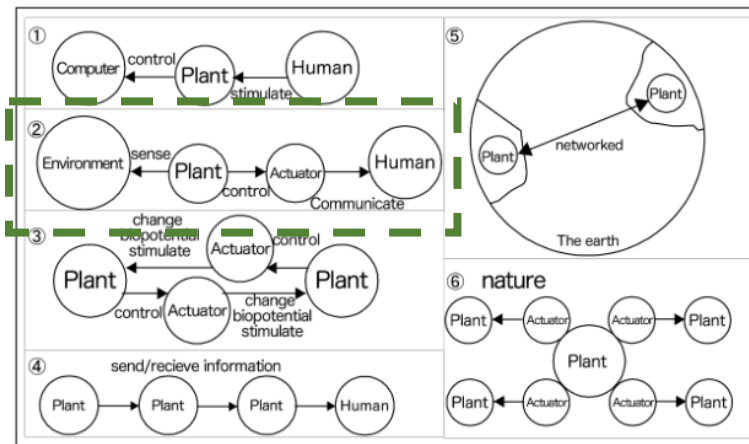


Figure 8 Pattern for utilizing (Kuribayashi, Sakamoto, and Tanaka 2007)

Figure 9 shows the information processing loop in which the role of plants and EPEs are assigned. The system is both biologically and computationally mediated. Environmental cues are first received and processed by plants through their internal computational process and

prompt changes in plant behavior and appearance. While it takes time for the naturally triggered transitions to show, artificial information processing is leveraged for detecting and harvesting the biological information from plants, which is, then, used to trigger the instant behavior change in Expressive Phyto-Extensions. From both plants and Expressive Phyto-Extensions humans can infer environmental conditions. Some of the advantages that Expressive Phyto-Extensions have over living plants are:

- 1) Immediacy – EPEs can display real-time changes if mediated by digital computation.
- 2) Readability – the change of configurations and motions of EPEs are more comprehensible compared to biomarkers. Understanding EPEs is easier than understanding biomarkers.
- 3) Activeness - EPEs respond to the changes in a more active and physical way, which could benefit not only plants, but also humans and animals around them.

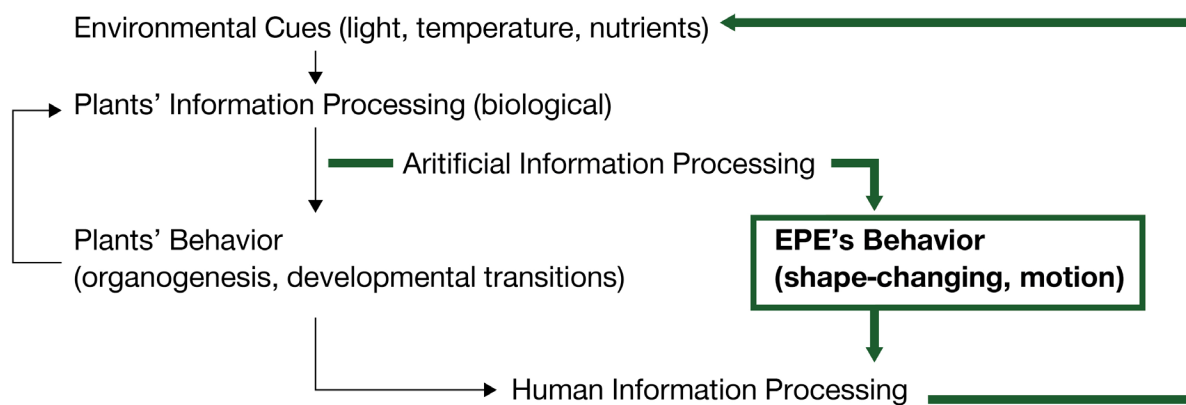


Figure 9 Information processing loop integrating EPE. The traditional process of environmental cues being processed through plants' internal computational process and prompting changes in plant behavior in the form of developmental transitions and organogenesis remains intact. Artificial information processing is integrated to extract biological and environmental information from plants. Expressive Phyto-Extensions relays this information to humans in a real-time, augmented way.

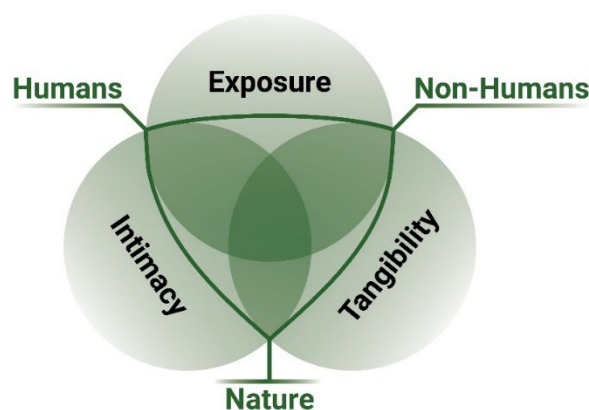


Figure 10 Diagram showing Expressive Phyto-Extensions are designed to transform the paradigms how human and plants interact. An approach that aims at exposure, intimacy and tangibility is promoted in the thesis.

EPEs are designed to transform the paradigms how humans, animals and plants interact. They are all about increasing humans' perceivability of the surroundings through more materialized exposure and intimacy. Essentially, they offer a new way for us to see the world.

3.1 Why tangible interface?

In the previous section, I have introduced the descriptions, functions, and characteristics by which Expressive Phyto-Extensions can be understood. Next, based upon the design visions of this thesis, I talk about why I choose to use tangible interfaces instead of digital ones.

First and foremost, what is considered as a tangible interface? According to Ulmer and Ishii, a tangible interface “gives physical form to digital information, employing physical artifacts both as representations and controls for computational media” (Ullmer and Ishii 2000). In their definition, they explicitly excluded digital representations, such as graphics and audio, as well as any interfaces that can be identifiable as “computers”. One example in the precedent review is *Botanicus Interacticus* (Poupyrev et al. 2012), which was excluded from the “tangibility” category. In that project, although not directly displaying digital data, the final output yet still yielded into visual and audio format. Thus, such projects are not considered as designing with tangible interfaces.

When compared to digital interfaces, the following three properties of tangible interfaces have made them a better fit for achieving the design vision of this thesis (Ullmer and Ishii 2000):

- The tangible interface is tightly coupled with underlying information mediated either biologically or computationally. EPEs are designed to directly and efficiently represent the plants' responses to environmental stresses. They function as active extensions of their biological host to 1) help them cope with various challenges 2) inform others of the changes.
- The tangible interface persists. It has material properties and holds the status. Borrowing terms suggested by Holmquist, Redstrom, and Ljungstrand (Holmquist, Redström, and Ljungstrand 1999), EPEs are not only “containers”, “tokens”, but more importantly, they are “tools”. Unlike digital information, the materialization of the interface often entitles it a more functional role other than merely displaying information. For example, on top of the very basic function of displaying information through their shape change, the motions of the EPEs can be leveraged to help repel pests, form shelters, etc.,.
- The tangible interface can afford a variety of associations with digital information. They can take on a wide range of physical forms as well as different level of abstraction. “A representational determinism is suggested – the form of a representation determines what information can be perceived, what processes can be activated, and what structures can be discovered from the specific representation.” (Zhang 1997) Compared to digital information that usually celebrates

clarity, tangible interface sometimes, on the other hand, embraces ambiguity. "Imprecision often prompted the human users' physical involvement with the materials being sensed." (Kuznetsov et al. 2011) In that sense, EPEs can better encourage inquiries into the environment, supporting outdoor learning experiences.

To further investigate into the concept of tangibility and understand how people react to novel interfaces that are attached to living plants. I carried out an experimental project called Flower Balloon in the summer of 2021.

Flower Balloon

In the summer of 2021, I initiated Flower Balloon project (see Figure 11). The project is a preliminary experiment that was set up to understand public reactions to novel artificial parts attached to living plants and how those tangible extensions affect the interaction between people and the plants. It is a fast materialization process to prove some of the concepts speculated in earlier stage of this thesis. The qualitative feedback collected from the experiment has substantially motivated the rest exploration of the thesis. It was very well received by the public and triggered many improvised new interactions between people and the hosting tree that were beyond the initial expectation.



Figure 11 Flower Balloon – 1) and 2) Flower Drying Process; 3) Flower Balloons attached to a local ginkgo tree in the community park; 4) and 5) people stopping by and interact with the balloons and tree.

Flowers

The process started with an intentional first step of collecting flowers in the neighborhood that I live (Maple Leaf @ Seattle). The thoughts of avoiding outsourcing flowers from somewhere else are based on following reasons:

- 1) I want to see how the local residents react to a novel presentation of familiar things they may own, see or simply pass by every day. Does it provoke new interactions? Does it catch attention or create chaos?
- 2) I want the flowers that are attached to the hosting tree to be fresh and seasonal so that they match the natural patterns that occurred during the time period when the project was implemented.

- 3) I select the most planted and owned flowers in the neighborhood as an informative representation of the local gardening/landscape scene.

I collected flowers on my evening walks and brought them back home. Using silica gel crystals to dry the fresh flower and storing them in air-tight container for 4-7 days to achieve best results. Dried flowers usually last for a longer time, which is suitable for the purpose of this project since I don't want the flowers look withered after a couple hours. Using silica gel to dry the flowers leaves them stay true to their form, color, and texture, compared to other flower drying technique, such as flower press, etc. Details of flowers can be perfectly preserved in this process, which is important for this project as I would like to present those flowers as realistic as possible so that the whole installation unfolds in a deceivable way that it makes people to think about the alternative biological relationship between the hosting tree and those "living" flowers and how they are interconnected.

After the flowers are dried, different species are purposefully selected to be put together, forming different bundles. The selection criterion is trying to diversify the species in a bundle as much as possible so as to create this alien/novel concept of one(branch)-to-many(flowers) relationship, which ties to a futuristic thinking of the Expressive Phyto-Extensions could be made of another species of living plants that is different from the hosting one.

Container:

The bundles are then placed into transparent inflated balloons. The original balloons were cut in half and sealed back again once the flowers are placed inside them. The balloons serve perfectly as the display container for the purpose of the project as they are visually minimal. They have this light and airy quality that makes it easy for them to fade into the environment and background. Yet they are not entirely invisible. The subtle boundaries defined by the balloons leave a refined space for people to take close-up looks at the flowers and be curious about how they "grow" from an irrelevant tree.

Hosting Tree:

I picked a hosting tree that is located in Maple Leaf Reservoir Park - the neighborhood park. It is a humble ginkgo tree that does not catch at all attention. It is an ideal hosting tree for its anonymity. I would like to see how the "newly grown" flowers on this tree would affect people's interaction with it, how does a novel interface can challenge people's original perception of this unknown tree.

Location:

The location is the neighborhood park located in Maple Leaf Neighborhood, Seattle. This park is a popular to-go place for local residents. They usually spend their evenings on both weekdays and weekends in the park, exercising, walking dogs, hanging out with families. Most people in the park are very familiar with and used to it. Nothing sticks out to trigger extra attention or curiosities. Its ordinariness makes it a perfect experimenting spot as sensations can be easily aroused by new and novel stuff.

Observation Results:

The Flower Balloons received huge reactions and triggered heated discussion among the local community. They were left attached to the ginkgo tree for 24 hours. They attracted a good number of people who were spending time in the park. A photo of the installation from an anonymous photo-taker showed up on a popular social platform and attracted more than six thousand views within a week (see Figure 12).

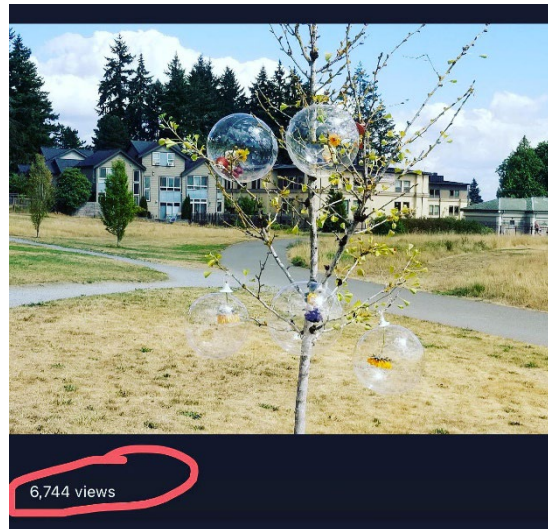


Figure 12 The Flower Balloon Project attracted more than 6k views on social media within five days.

I made an in-person observation for the first two hours after I put up the balloons. People stopped by at the tree and started to ask questions, such as “Are the flowers real?” “What do the flowers do on the tree?” “How are the balloons attached to the tree?” and “How did the flowers get into the balloons?” Due to Covid-19, a lot of people chose to stand next to the Flower Balloons and just looked at them. Nevertheless, there was still a good number of people that were very tempted to interact with the balloons through touch and feel. From the observation, I noticed that people really enjoyed seeing and learning novelties that happen in nature. The Flower Balloons brought about a lot of beneficial byproducts, such as they substantially increased the outdoor time people spent, they encouraged heated discussions regarding the flowers and the trees, etc. A lot of people took photos with the Flower Balloon either individually or as a group. Some people lingered around and started talking about their childhood memories that were associated with those flowers and trees. Parents take their kids outside into the park solely for seeing the Flower Balloons at a closer distance.

Despite the sensations it triggered locally, it also revealed a lot of gaps and discrepancies between my initial goal and the interactions that occurred in real life. For instance, people were more attracted to the flowers inside the balloon due to their novelty. They still tended to ignore the hosting tree as it might appear as a mere hosting substrate. This does not align with my original goal of drawing people’s attention onto the humble hosting tree that has been long overlooked. People also tended to see it as an artistic expression instead of a

technological possibility. The installation itself did not trigger any conversations regarding ecological balance, plants care and maintenance or human-environment relationship. Those observations are significant and profound for my following explorations and are informative for future work.

3.1 Material and Interface Selection

As mentioned in previous chapters, the design of the interface between human and plants here I explore should exhibit following features: 1) compatibility with natural environments 2) minimal impacts on the plants 3) versatility in displaying information.

The design and engineering of inflatables can lead to versatile shape-transforming structures without requiring direct embedding of electronics. Air or water pressure can be used as energy sources for the actuation process, both of which can be universally sourced in a natural setting. Depending on the material selection and design solution, the inflatables can be light weight and compliant enough to have minimal interference with the growth of plants.

Pneumatically actuated systems have been well explored in multiple fields. Their capability of dynamic shape outputs with a variety of transformable materials has made them popular among research communities who design and study physical objects that transform to serve different functional purposes. Previous works have explored a wide range of materials that work with pneumatic actuation mechanism. Materials that range across categories including polymer, composite, and ceramics, have been studied and used for fabrication. Shape-changing objects made from different materials exhibit various stiffness, durability, transformability. They also affect other factors such as actuating efficiency, sustainability, scalability, responsiveness etc.

In this thesis, I chose to use ½ mil clear flexible Polyethylene Film as the basic testing materials due to their wide availability and low cost. They satisfy the features that I am looking at in designing Expressive Phyto-Extensions, such as being light weight and compliant. It works well with either air or water for actuation. Compared to heat-sealable fabric, the Polyethylene films are thinner and easier to work with as it takes less tuning of the machine parameters when fabricating air-tight pouches. However, they are not biodegradable or biocompatible, which goes against the sustainable vision in this thesis. The choice of the material is solely for rapid prototyping to test out the functionality of EPEs and they will be replaced by greener materials in the future.

3.2 Prototypes

The outcome of the exploration of Expressive Phyto-Extensions design and engineering is three assembled prototypes that all center the plants. They extend the plants' capabilities either in coping with environmental stresses or actively conveying what they sense to humans and animals. Their intended functionality could be perceived through an understanding of specific scenarios in which our ecological system is being challenged.

Inter-species Communication (see Figure 13)

Actively relaying information to animals when danger is detected.

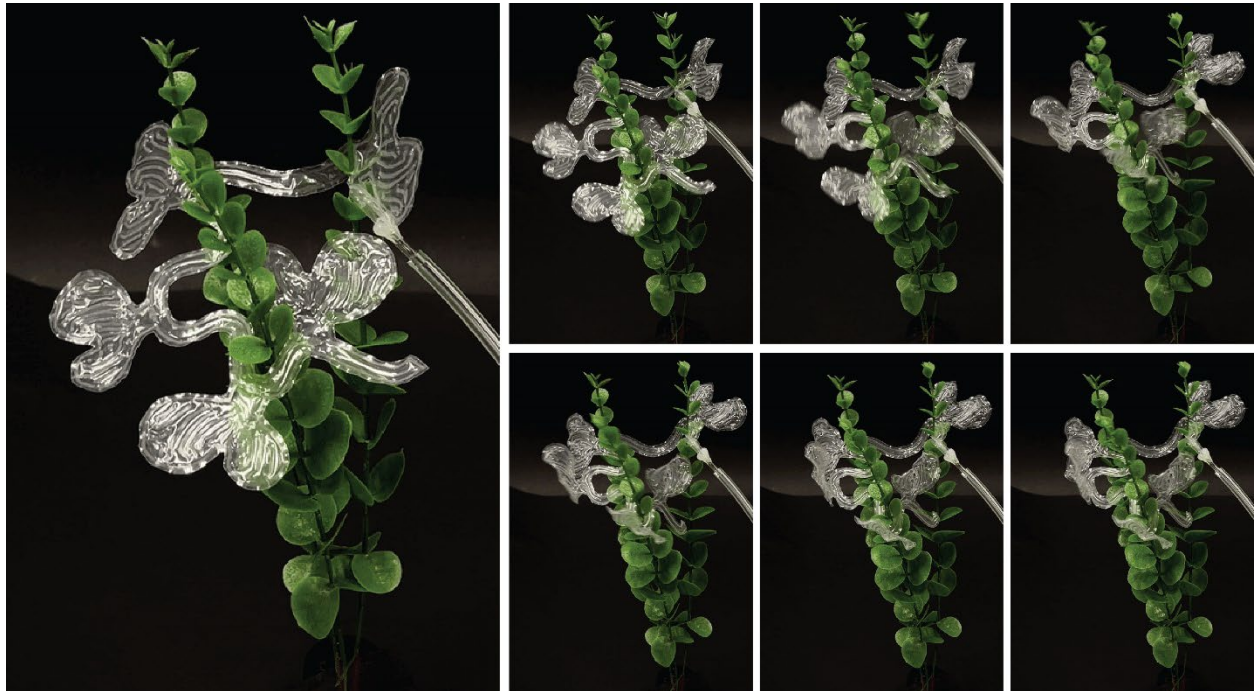


Figure 13 Inter-species Communication Prototype

Description: Milkweed (genus *Asclepias* -Family *Apocynaceae*, subfamily *Asclepiodeae*) is a plant that emits sticky white substances when their leaves are damaged. The substance produced by milkweed is a cardiac poison to most vertebrates. While milkweed might be poisonous to other species, it is a host plant for the monarch butterfly (*Danaus plexippus* L. Lepidoptera: Danainae) and prevent their larvae from being consumed by potential predators. Monarch butterflies show preference to some milkweed species. (“Monarch Butterfly Habitat Needs” n.d.)

The problem: In recent decades, a plummeting number is shown in the population of monarch butterflies. According to an estimate in 2012, there might be “an 81% decline in monarch production the Midwest from 1999 to 2010” (Pleasants and Oberhauser 2013). Several plausible causes leading to this decrease have been discussed among scientists, one of which is the temperature increase due to global warming (Faldyn, Hunter, and Elder)

2018). The increase of the temperature in the environment induces the elevated concentration level of cardenolide. Although more toxic chemical compounds may “confer a greater defense against predators”, too much of them could lead into health issues and even mortality of monarch butterflies (Faldyn, Hunter, and Elder 2018). Monarch butterflies locate milkweed through a combination of their sense of sight and smell. Females identify milkweed before laying eggs on it. There is no way for them to have a good estimate of the concentration level of cardenolide. And with that, the changed quality of the plants could become ecological traps for those bright colored epic creatures.

The solution: To prevent further decrease in the population of monarch butterflies, the milkweed can help to warn off the butterflies when the cardenolide concentrate level within them has been over a tipping point that might cause actual harm to the monarch larvae. This extension circles around the plant to cover as many angles as possible. It is designed as a linear structure threading together multiple fanning components. The fanning components are connected to the main vein through diamond-shaped hinges which allow two-degrees of freedom in their motion. If the concentration level surpasses certain threshold, the Expressive Phyto-Extension generates a rapid motion around individual milkweed to prevent females from landing on the plant and laying eggs when sensing the butterflies are around. This extension could be coupled with sent-releasing as an add-on function to prevent the monarchs from locating them through smell. It helps to actively relay plant-related information to animals.

Protecting / Sheltering (see Figure 14)

Active physical response to environmental stress.



Figure 14 Shelter Prototype

Description: Blueberries (genus *Vaccinium*) are a widely distributed and widespread group of perennial flowering plants that are native to North America (“Blueberry” 2022). They are regarded as one of the foremost health foods and have great commercial value. In the state of Maine, blueberries are important to the local economy and culture. They are one of the hallmarks of Maine cuisine and “ten percent of all North American blueberries, both wild and cultivated, are from Maine”.(Kayser, n.d.).

The problem: The climate shift that has been measured globally including the change in precipitation and temperature affects the growth and health of blueberries in multiple ways. Research suggests that possible challenges such as a greater presence of pests due to the rising temperature in winter and potential risk of bloom destruction due to late spring frosts (Lobos and Hancock 2015) can cause real ramifications for the crop treatments and harvest. For example, “*Drosophila* (*Drosophila suzukii*), a type of fruit fly native to Asia, was first detected in Maine in 2012 and poses an emerging threat to small fruit production systems (Kayser, n.d.)”. Another example, “Maine’s growing season has extended by two weeks since 1950, largely due to a longer fall season before frosts.” This change stimulates early plant development before the final spring freeze, and results in frost-kill (Kayser, n.d.). Natural physiological adaptations can potentially help blueberries to meet these challenges genetically, just like how blueberries have evolved in this region through history, but they can be slow and inefficient.

The solution: While waiting on the adaptations of blueberries’ genotypes, growers and breeders can use some immediate plant wearable technologies to help blueberries to get through this transition. The Expressive Phyto-Extension has three branches and one-degree-freedom hinges along each branch. When actuated by sensing the abnormal temperature or proximity of pests, the branches curl up, forming coverage over and around the blueberries. The exterior of the extension is made of water-proof fabric and the interior side is made of TPU film. Due to the elasticity of TPU film, when filled with air, the pouches snuggle tightly but softly around the fruit without causing damage. The stiffer exterior can help not only protect the fruits from potential pests but also against harsh weathers.

Assisting Horticulture/Agriculture (see Figure 15)

Co-creating/collaboration with humans

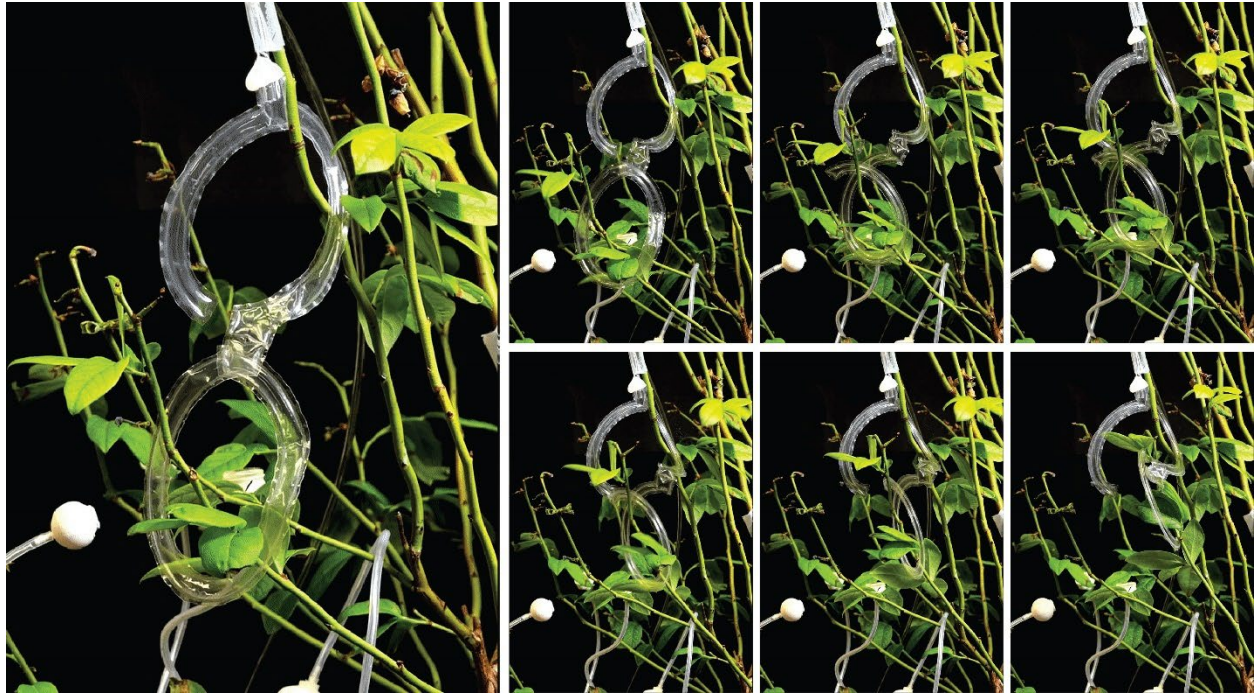


Figure 15 Horticultural Assistance

Description: Grapevines requires training to achieve balanced light exposure, air penetration, leaf transpirations, etc., in order to get higher yield potential, optimized leaf area to fruit ratio and better disease control (Reynolds and Heuvel 2009).

The problem: The training system itself is a complex one that requires knowledge such as vine photosynthesis, sugar and acid metabolism, micrometeorology, and many other fields(Reynolds and Heuvel 2009). Commercial training system is regionally available but might not suit hobbyists' needs. Common grapevine training systems usually come in the form of a trellis, arbor, or a fence (University n.d.). Although upfront planning can help to alleviate the challenge of entangled and intertwined vines that can be hard for pruning, it is after all hard to avoid without careful consideration and rich experience when constructing the system.

The solution: The Expressive Phyto-Extension is designed in a series of oval loops that are connected through diamond-shape hinges. When actuated by sensing undesirable light exposure or problematic air penetration, they curl up in different degrees. The entanglement between the EPE and the vine plant enables the EPE to operate gently on the vine plants and move them in alternative directions. When chained up in multiples at a larger scale, this EPE design can be distributed across vine canopy and assist with training the local growth of the vines computationally.

4. Design Workflow

In order to understand what specific functions the Expressive Phyto-Extensions should take on in response to different environmental stresses and how to choose their physical forms from myriad possibilities to achieve the aforementioned design goals, this thesis presents a workflow that comprises 1) a context-driven design approach, together with 2) an Expression Dictionary that assists people from various backgrounds to get started with designing and engineering Expressive Phyto-Extensions using inflatables with lower and fewer barriers.

4.0 Design Challenges

Before jumping into the details of the workflow, I would like to talk about the design challenges faced by designers when designing interactions that center around plants and “human/animal-environment” relationship.

More-than-human-centered Approach

As mentioned in Chapter Two, most projects that have been discussed hold a human-centered view when designing the interaction. Projects, such as *Botanicus Interacticus* (Poupyrev et al. 2012), *Cyborg Botany* (Sareen and Maes 2019), treat plants as novel interactive components whereas the vitality and longevity of the plants are less of a concern. Centering human’s needs is a constant topic to explore as we mostly observe the world from our own perspective, and we want to better interact and relate to our environment for the sake of the survival of our own species. Note that here “more-than-human-centered” is being used instead of “decentering human”. This thesis is not challenging designs as such should be deprived totally of human needs and perspectives, which could hardly be achieved anyway. What I am trying to explore through a different design framework, instead, is the possibilities brought by new ways of thinking that are beyond human beings and see how things could be different if we start to treat the “human-environment” as a whole continuous organic piece, instead of discrete components.

“In a networked world with many connected actants – both human and non-human – the notion of human centered ceases to be useful. When designing for networked ecologies prescribing a unique center cannot properly characterize the design space.”(Coulton and Lindley 2019) According to Gibson, a single, frozen field of view provides only impoverished information about the world (Gibson 2014). Considering multi-species perspective does not take humans out of the equation. Rather, the goal of taking non-humans into the loop is to blur the boundaries of people and others, “emphasizing the interconnectedness that is inherent in human/nonhuman assemblages”. (Smith, Bardzell, and Bardzell 2017) Reframing the questions proposed by Laura Forlano, what if, rather than understanding the needs of humans, designers are tasked to understand what plants want? What pollinators want? "What expertise or theories might be needed in order to address this problem? What models, methods, frameworks, and sensibilities might be essential for exploring possible solutions? What new languages, questions, and alternatives might emerge in the pursuit of such a project, and how might it form the basis for new kinds of design knowledge?"(Forlano n.d.)

Projects such as *The Plant Sex Consultancy* (Lin et al. n.d.) have made attempts of “designing for the non-human other”. In the project, the authors expressed the challenges that they have faced when designing for non-human subjects, for example, “lack of first-person experience”, “limited knowledge on plant cognition”, etc. Gibson has once describe in his famous book *The Ecological Approach to Visual Perception* (Gibson 2014), “we shall treat the vegetation of the world as animals do, as if it were lumped together with the inorganic minerals of the world.” Moreover, he says “plants in general are not animate; they do not

move about, they do not behave, they lack a nervous system, and they do not have sensations.” Although The Plant Sex Consultancy team have extensively studied plants as subjects of their own and made the knowledge about plants foreground of the process, they, nevertheless, had to boil down to intentional anthropomorphical biofictions as end products. They tried to appropriate human-centered design methodology onto plant-centered design. Yet, in the end, they had to admit the “irreconcilable differences” between humans and the Other. Here, this thesis is not intended to challenge this “inanimate” property of plants from physics, biological, chemical or any other angles. Indeed, the research seeks to “promote new ways of approaching technology development that accounts for multiple and heterogeneous standpoints”. (Smith, Bardzell, and Bardzell 2017) This move does not only simply imply ethical obligations. Rather, it is a move for having design being more supportive for complex entanglements between humans and nonhumans. We are not the only species that “create meanings.” (Smith, Bardzell, and Bardzell 2017)

A “more-than-human-centered” design view, fundamentally, is to understand how humans can better relate to the rest of the world and to better excavate the multiplicity of values and interests that do not center around only humans. It refuses an absolute dualistic view of objective and subjective, knowing that the boundaries between humans and their environment are fluid and the two are exchangeable in a sense. “Ecologists have the concept of a niche.” (Gibson 2014) And it refers more to how the animals, including men, live than where they live. And Gibson defines a niche as “a set of affordances” (Gibson 2014). A “more-than-human-centered” approaches is to add more affordances¹ to this “human-environment” entity so that the many unoccupied “niches”, the many offerings from our environment could be better perceived and the inadequacy could be further understood.

Claimed by Laura Forlano, when we adjust “our fundamental understandings of human and non-human knowledge and ways of being in the world, it is likely that we will also develop corresponding design methods, frameworks, and practices that better address the challenges we face as a planet.”(Forlano n.d.) And this thesis attempts to further this thread of efforts, which has been initiated by projects such as the Plant Sex Consultancy (Lin et al. n.d.), Infotropism (Holstius et al. 2004), Babbage Cabbage (Fernando et al. 2009), in developing a new design framework that considers that following questions suggested by Laura Forlano (Forlano n.d.):

- “1) Who or what – human/nonhuman, human/animal, individual/organizational/network – are the user(s), and for whom or what should the design be desirable?
- 2) How, and in what ways – competitively/collaboratively, hierarchically/horizontally – are capabilities, agency, and power distributed across human, machines, and natural systems?
- 3) What new knowledge(s), questions, stakeholders, and partnerships are needed in order to adequately design for this problem?

¹ “The affordances of the environment are what it offers the animal.” (Gibson 2014)

4) How are ethics, values, and responsibilities reflected and embedded throughout the design process?”

In this thesis, human beings, animals, and plants comprise three different types of users. Their experiences and interests, which were both regarded as triggers and impacts, were taken into consideration when framing design scenarios and defining prototypes. Challenges when considering non-humans in the process, such as those mentioned in the Plant Sex Consultancy project – lacking first person experience and limited knowledge of plants/animals’ cognition – motivated collaborations with domain experts and exploration of newer technologies. Though might not be fully conquered, design challenges of such unfold an aspiring space that can be further explored through partnerships as they may bring in new values.

Sustainability

With the belief that “human-environment” is one continuous entity that rejects dichotomy, sustainability inevitably becomes a concern of this thesis. Jedediah called in his book *After Nature* (Purdy 2015) our current environment - “the planet’s landscapes, forests and fields, along with the species that inhabit them”, a mélange of those created by us. He says, “The natural and the artificial have merged at every scale.” However, in recent years, anthropogenic actions that detrimentally alter our environment have been increasingly prevalent. “For example, off the coast of Western Africa, climate-change-induced environmental variability and overfishing have created cool, chlorophyll dense waters, usually indicative of healthy fish populations, that are devoid of fish. This has created an ecological trap for endangered African penguins, which use chlorophyll density as an indicator of good fishing grounds.” (Faldyn, Hunter, and Elder 2018). Therefore, it seems to be a necessity to design interactions that provide more affordance between us and the environment to help promote the awareness of the environmental and ecological stresses that we have been overlooking. It is the parallel evolvement of the ecological environment and human interactions with it this research is looking at and studying. The built environment is understood as a synthetic expression of direct and indirect human interventions upon ecological systems and their processes. Natural systems that used to be considered as operating at the scale of years, seasons and days are now capable of giving instantaneous and dynamic feedback, thanks to the advancing technologies.

“If Nature were a place, we could not find it. If Nature were a state of mind, we could not attain it. We are something else, and so is the world.”

--- Jedediah Purdy, After Nature

Considering the inseparable relationship and the interchangeable boundaries between humans and the environment, to Tony Fry’s point of view, nowadays design should be about decisions made toward a more sustainable future. “Fundamentally, design has to become a

form of decisionism toward futures able to demarcate between acts and objects of creation and destruction. Such action cannot be predicated on moral judgement (idealism). Rather it has to be the consequence of a neo-materialist hermeneutics underpinned by ontological inquiry (radical empiricism)." (Fry 2005) Eli Blevis sees this as a set of latest and urgent design value that designers should be considering and balancing with respect to other design values when making design decisions for our collective futures. He defines design values as "an act of choosing among or informing choices of future ways of being".(Blevis 2007) In order to avoid an undesirable future, a more critical design framework should be thought through, in which sustainability plays an important role. He describes sustainability as an "aesthetic of well-cared-for systems." It is an advocate for a value-rich design approach. This approach includes "aspects of the environment, public health, social equality and justice." (Blevis 2007)

Sustainability in design apparently is still in its infancy. Jennifer Mankoff, et al, building upon the notion that "sustainability can and should be a central focus of [the field of human computer] interaction", advocate that "sustainability cannot simply be an afterthought, but instead needs to be considered throughout the lifecycle of a project." (Mankoff et al. 2007) Although discussed within the domain of HCI, this notion is indeed applicable to a broader scope of design activities. Jennifer Mankoff, et al, talked about two approaches to address sustainability, specifically, in interaction design field. One is "Sustainability in Design", and the other is "Sustainability through Design". Sustainability in Design refers to considerations regarding issues such as "energy footprint, reduction, reuse and recycling". While Sustainability through Design addresses issues such as "how to support sustainability lifestyles and decision-making through the design of technology." (Mankoff et al. 2007) A lot of precedents I talked about in Chapter Two have adopted the latter approach, partially due to the symbolic significance of plants themselves. Projects, such as Infortropism (Holstius et al. 2004), Babbage Cabbage (Fernando et al. 2009), try to convey environmental-related information through the plant-based displays.

In this research project, "Sustainability through Design" is certainly one fundamental part of the framework that guides the design. "From the perspective of design reasoning, one way to think about SID (Sustainability in Design) is as the notion that representations and interpretations of interaction design should as well denote and account for the effects of a design on the environment and sustainable behaviors."(Blevis 2007) Motivating more sustainable behaviors based on better understanding of our environment is one of the key design goals in this research. What kind of environmental information does the artifact reveal to people and how does it affect people's understanding and behavior? How do these new understandings and awareness affect people's preferences and what kind of changes do they trigger in human-environment relationship? Expressive Phyto-extensions are conceivably designed to help better answer those questions.

“Sustainability in Design” is less of a focus in the current phase of this research. Nonetheless, addressing issues such as renewable materials, recycling the devices and clean energy for actuation is of certain interest in the future.

4.1 Workflow

The workflow adopted by this thesis (see Figure 16) is consisted of two parts: 1) constructing specific contexts to define EPEs’ functions 2) designing and fabricating inflatables interfaces that have the designated function.

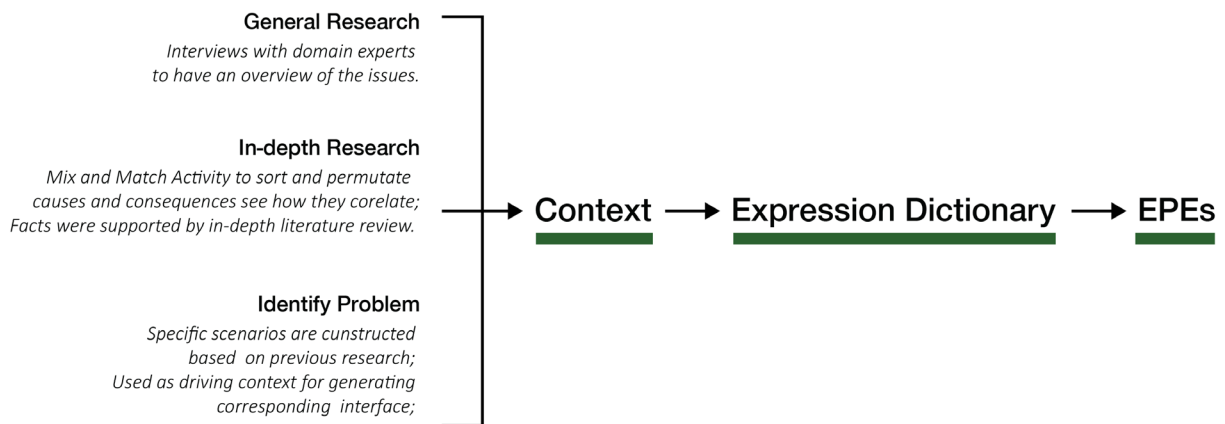


Figure16 Workflow that is consisted of constructing context, identifying fabricable components and design the assembly.

Context-driven Design

A mixed method comprising interviews, analytical research and scenario construction is used to identify the pressing issues concerning plants and their environments. These activities took place in a sequential fashion so that they progressively provide me a better understanding of plants as a subject and identifies external considerations from different levels. This sequence helps to funnel through a broad range of ideas, from ambiguous and abstract to clear and concrete. With different partnerships and expertise introduced into the process for understanding the context, it helps to cope with the dearth of plant and environment related knowledge and leads to a rich design-space exploration and a sound decision-making process.

Interviews

As mentioned by Lin, et al (Lin et al. n.d.), it is always true that designers as humans don’t have the firsthand experience of non-human organism, thus making it hard to understand the subject that they are designing interactions for. Realizing the plants’ needs might be radically different from those of humans, this thesis takes a stab at alleviating this irreconcilable issue by introducing expertise in the early stage of the design process.

I conducted two interviews with people who interact with plants on a regular basis. One is an urban forager as well as a youtuber, who studies nutrition at college and knows about almost all wild edible plants within Pittsburgh area. The other is an urban farm manager who does farming plans and grows produces on a piece of urban lot in the city of Pittsburgh.

“Although speculative, experts are often consulted when building these scenarios, as David Kirby points out in a fascinating chapter about distinctions between what he calls speculative scenarios and fantastic science in his book Lab Coats in Hollywood; the role of the expert is often, not to prevent the impossible but to make it acceptable.”

----Speculative Everything: Design, Fiction, and Social Dreaming

The interviews are semi-structured. Although questions were prepared beforehand, new questions were added on the fly as the interview continued. Most questions were designed as open-ended questions and the interviewees are free to steer the content of the interview to cover the issues relevant to them. (See Appendix – Interview Transcripts) The goal of the interviews is to understand the current common challenges they face when interacting with plants given their rich knowledge in plants yet different domains of profession.

Several things stood out from the interview:

- How the two interviewees interact with plants is hugely impacted by local environmental and ecological condition.
- They interact differently with different species. So species matter.
- When they decide how to interact with the plants, they subconsciously take on a more-than-human perspective. Meaning, they also consider the impacts of those interactions on not only humans but also animals.
- Soil contamination and food safety are two major concerns. Tools that can help them identify toxic overload will be most helpful to their practice.
-

Mix and Match

Based on several take-aways from the interview, I designed the Mix and Match activity to dig deep into local environmental concerns, plant species and environmental stresses they are prone to. Therefore, in this activity, there are groups of cards (see Figure 17) that cover environmental concerns, plant physiological responses, interaction types and plant users (species). I used the activity to explore possible and reasonable interaction loops between humans, plants, and animals by mixing and matching up different cards based on my understanding and knowledge as a result of in-depth research.

The goal of this activity are followings:

1. Better understand plants’ biological changes in relation to their species and environmental changes.

2. Better understand how the plants' biological changes affect the interactions between the plants and humans as well as plants and animals.
3. Better understand what are the attractions or detractions EPEs could provide for specific hosting plants? And for what purpose?



Figure 17 Groups of cards designed for Mix and Match activity. The first group are cards indicating various environmental factors. The second group of cards list out different physiological and morphological responses plants give out when their environment changes. The third group of cards list out different type of users the specific interaction is concerned with, which include humans, animals, and plants.

This analytical process led to a bigger yet grounded space for aspiration and imaginations, which helped to find solutions that go beyond conventional ones. This sense-making process is an inquiry through design that enables discussions on the opportunities and risks of the prototypes to be proposed. This activity helped me to build towards better articulated scenarios with the right level of dynamics, expressions, and nuances (Rozendaal, Heidingsfelder, and Kupper 2016) in the next stage. The results from this process provided meaningful horizons for the prototype development and a better judgement of doable versus non-doable, necessary versus unnecessary.

Scenario Construction

Scenarios that describe the relationship between human, plants and animals are produced through sketching process. They are based on a synthesized analysis from previous activities. In the scenarios, a concrete interaction loop is depicted where functional roles of EPEs are assigned. The scenario constructing process is essential in helping me to first understand and then design the extension in a sense-making way. Figure 18 shows a series scenarios were pictured with EPEs catered to take on unique functions for responding to the situation.

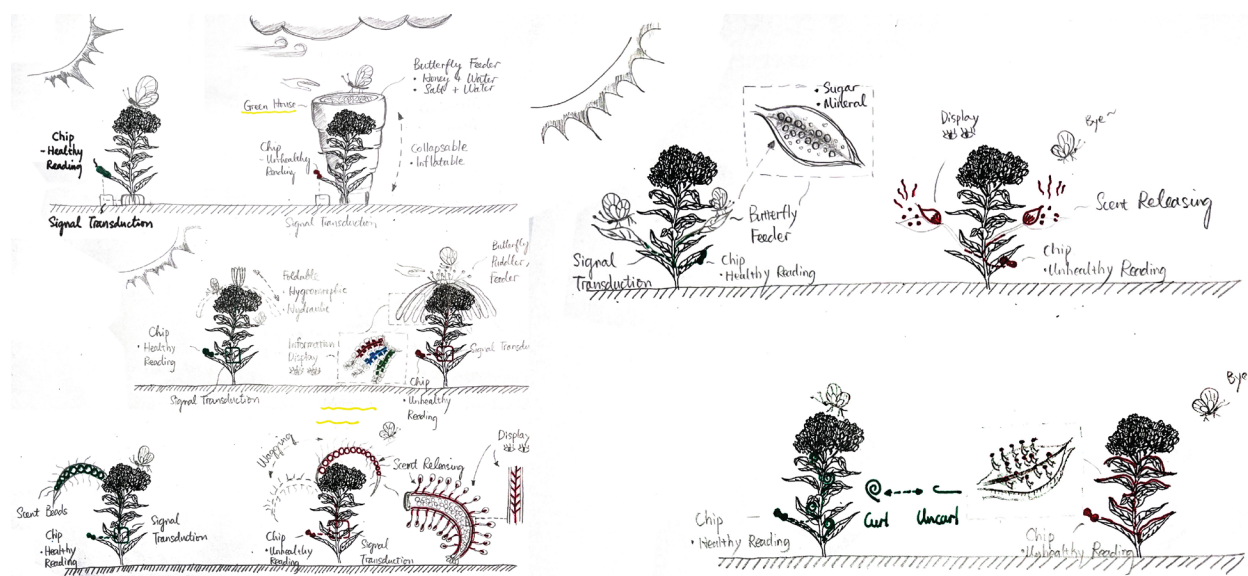


Figure 18 Scenario Construction sketches.

Expression Dictionary

Why an Expression Dictionary?

The topic of facilitating the design and the fabrication in fabrication-oriented computational design has been a trendy field of inquiries in recent decades (Ou et al. 2016). For example, a team from Zurich, led by Melina Skouras, et al, presented a method of a dedicated algorithm that “allows a user to automatically create physical replicas of digitally designed characters using rapid manufacturing technologies” (Skouras et al. 2013). Their method yielded “physically-fabricated prototypes with different types of actuators and materials”. Since there is not always going to be a physical counterpart reachable in the material world of that created in the virtual world, they asked “that the character be composed of a set of given base materials and that example poses should be reachable using only a limited number of external actuators.” In the paper *Motion-Guided Mechanical Toy Modeling* by Zhu, et al (Zhu et al. 2012), the team stated their goal as to “allow people unfamiliar with mechanisms to design and fabricate their own mechanical toys”.

My work shares some of these goals, such as lowering the barriers for people from various backgrounds so that they are able to design and engineer the extensions, enabling rapid

prototyping to achieve desired function, etc. However, I take a significantly different approach. Instead of admitting different types of actuators and materials, Expressive Phyto-Extensions exclusively deal with inflatables and sheet materials. The physical output is for emulating the functional property of its animated counterpart instead of a one-to-one literal mapping regarding formal characteristics.

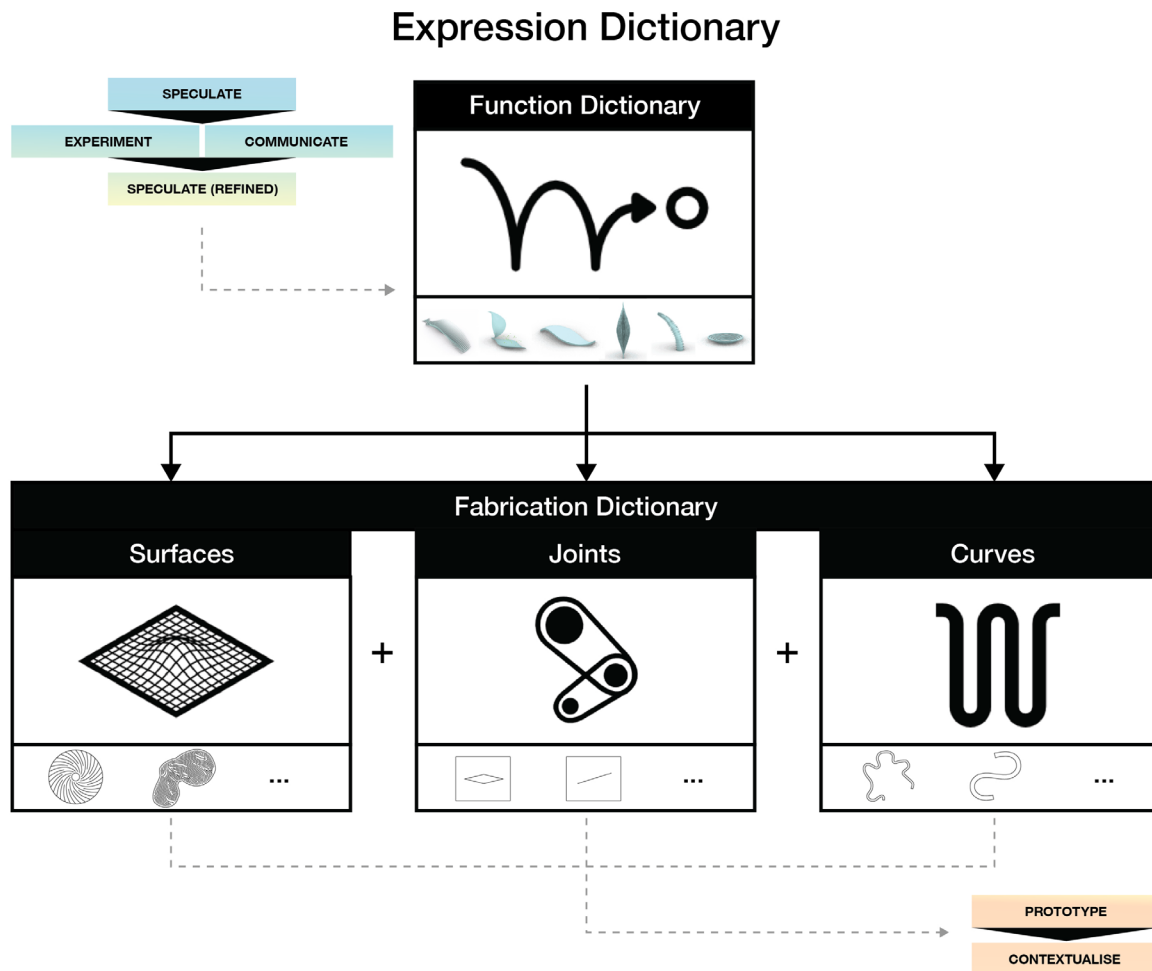


Figure 19 Structural Mapping of Expression Dictionary

Expressive Phyto-Extensions are tangible interfaces that are made of inflatables. They are versatile in displaying different shapes and motions, as well as light in weight and compliant in structure. However, designing and engineering Expressive Phyto-Extensions can be daunting to newcomers. There exist plenty intricacies both in designing and fabricating inflatables. Obtaining an exact match between an ideal functional motion and a physical inflatable interface is nontrivial. If a desired motion or form were to be translated into a fabricable inflatable piece, it would potentially mean the involvement of heavy math and physics, which could greatly hinder the prototyping progress for designers or people from other backgrounds. It requires a thorough understanding of subjects, such as how the pneumatic actuating mechanism behaves differently with different sheet materials, how 3D

transformations can be translated into 2D geometries and patterns and vice versa, what is the extent of geometric and volumetric complexity inflatables are capable of, etc. The goal for proposing a resourceful dictionary with compiled geometries and motions is to provide rapid strategies for designers to prototype different inflatable interfaces catered to unique functions. It is aimed at facilitating the gap between a functional goal derived from a constructed scenario and the actual fabricable geometries/patterns that are suitable for fast prototyping. It pertains more to fast approximations rather than a literal one-to-one embodiment translation. Therefore, I propose an Expression Dictionary that consists of two subgroups (see Figure 19) – a Function Dictionary and a Fabrication Dictionary, from which designers can

- 1) Given a specific scenario, specify the best-fit functional goals from the Function Dictionary.
- 2) Select fabricable components from Fabrication Dictionary that can be assembled into an approximate match of the previous selection.
- 3) Scale and arrange the components into one assembly and fabricate the output.

Function Dictionary

The animated gestures in Function Dictionary are derived from previous research. Through understanding some of the pressing environmental and ecological issues, those functional gestures represent top-level features that Expressive Phyto-Extensions can cater to in order to help plants actively respond to the environment and communicate plant-detectable information to humans and plants. Note that this is an expandible dictionary, designed to admit more functional gestures as different issues emerge and different urges need to be addressed. What is presented here in this thesis is not exhaustive.

Six functional gestures are selected as listed in Table 4. The necessity of having a dictionary as such is because a combination of linguistic and pictorial elements for representation can help to deliver an active statement dealing with the objects' inherent qualities and functions important to people's understanding (Vihma 1990). The elements in the Function Dictionary work as visual guidance and assistance for designers before they jump into figuring out abstract geometric composition on a piece of sheet material. For example, the Collapsible resembles a container thus indicating potential sheltering function; similarly, the Folding shows a large coverage underneath the structure, which can be good for shielding; the Wagging and the Waving could be ideal for repelling unwanted bugs or animals, while the Releasing can be implemented with special smell that might either attract or repel animals; the Extending demonstrates compliance that can possibly be utilized in confined and unreachable space, etc. All these elements have semantic meanings, and they are intentionally described in a literal and straightforward way.

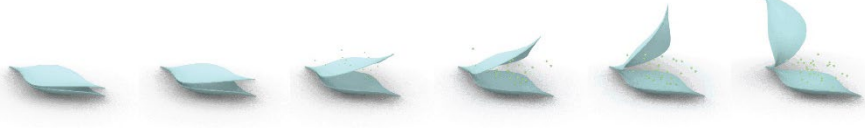
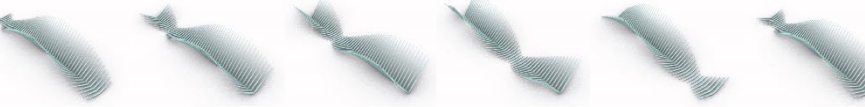
Transformation	Function	Applicable Scenario
 Figure 2 Collapsible	Sheltering	Harsh Weather
 Figure 3 Wagging	Repelling	Pests
 Figure 4 Folding	Shielding	Harsh Weather
 Figure 5 Extending	Reaching, Staking	Horticultur, Agriculture
 Figure 6 Releasing	Repelling, Attracting	Pollinators, Pests
 Figure 7 Waving	Repelling	Pests

Table 4 Types of Functions

The elements in the Function Dictionary not only help to inspire the form factors EPEs should consider but also help to alleviate the difficulty in picturing and designing motion mechanism of the inflatables, especially when dealing with a process that involves transforming 2D to 3D, static to moving. The gestural motions exhibited in the dictionary indicate the type of the shape-changing qualities the inflatables need to emulate in order to achieve the functional purpose. When testing with different linkages and assemblies in the next step, they are great references for designers to go back to and compare against, knowing the fabricable elements can only approximate the gestures instead of perfectly recreate them.

Fabrication Dictionary

Inflatables can take on diverse forms and can be actuated into a variety of volumes. Previous research has extensively studied the relationship between geometries, patterns, materials, and transformation mechanisms. For example, AeroMorph by Ou, et al (Ou et al. 2016), developed “a design, simulation, and fabrication pipeline for making transforming inflatables with various materials”. The team thoroughly studied the hinge mechanisms and defined three hinge types to generate various bending angles. BlowFab (Yamaoka, Niiyama, and Kakehi 2017) also played with patterns to achieve horizontal bending effects with different degrees of curvature. Printflatables (Sareen et al. 2017), on the other hand, studied a folding technique to create mountain patterns which then result in angular bendings for fabricating larger scale objects out of fabrics. Nevertheless, the process of designing and fabricating inflatables has its own limitations. First of all, imagine one has a target shape and wants to map it directly into an inflatable structure. This requires a math-heavy simulating and optimizing process and the final output as a computed result is not guaranteed for easy fabrication. As an example, a project led by Skouras, et al (Skouras et al. 2014) presented a design system that enabled users to fabricate inflatables from calculated flat sheets. Although being able to achieve very diverse results, the fabrication requires users to stitch flat sheets together in a particular way, which is time-consuming. Panetta, et al (Panetta et al. 2021), on the other hand, proposed a more general strategy that enables users to achieve various forms by fabricating inflatables in one patch. However, even for a sophisticated algorithm as theirs, a clear limitation is that, for some 3D shapes, their “metric distortion eventually exceeds the bounds realizable by the limited air channel contraction”. This motivates the necessity for establishing the Fabrication Dictionary proposed in this thesis to help people from different backgrounds with rapid testing out ideas for EPEs, freeing them from complex mathematical calculations and the inherent limitations of sheet materials and inflatables. With the compiled vocabularies provided in this Dictionary, designers will be able to:

- 1) Fast prototype EPEs by selecting and rearranging given components.
- 2) Achieve compounded assembly that approximates the functionality required in a given context and overcomes the limitation of the inextensibility of sheet materials.

There are three categories in Fabrication Dictionary – joints, surfaces, and curves. This thesis referenced some of the geometric patterns from precedents including AeroMorph (Ou et al. 2016), BlowFab (Yamaoka, Niiyama, and Kakehi 2017), Julian Panetta’s work (Panetta et al. 2021) and Emmanuel Siefert’s work (Siéfert et al. 2019). Those geometric vocabularies are appropriated and refigured according to the materials, fabrication capacities, and functional purposes for this thesis.

Joints

Joints are a type of connector with which designers can connect exactly two links (Lynch and Park 2017). Depending on the choice of the joints combined with the design of the linkages' geometries, designers can effectively define a one degree of freedom rotational hinge. And they are all comprised of simple shapes. By placing those joints components at different locations in an assembly, the inflatables can achieve out of plane transformation in multiple dimensions when actuated.



Figure 20 Buckling



Figure 21 Contracting

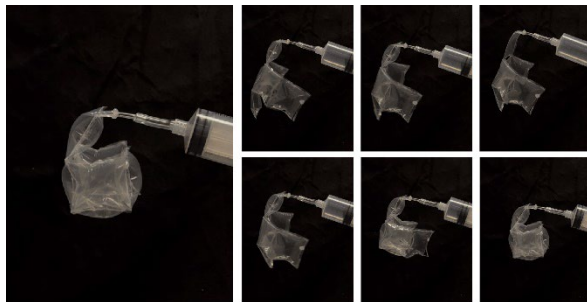


Figure 22 Bending

Buckling (see Figure 20)

Buckling is a deformation caused by axial loading. This component as shown in Figure 28 displays buckling motion (Yamaoka, Niiyama, and Kakehi 2017) when inflated. Due to the constraint from the material's inextensible property, when inflated, the straight side does not stretch while the finger side buckles towards itself. It can be used for creating different angles of curvature in linear elements. The proportion, scale and distribution of the fingers impacts the bending angle of the component.

Contracting (see Figure 21)

This component has fingers on both sides instead of one, which allows a contracting motion when inflated. The gaps between fingers allow the component to be compressed in axial direction when air pressure is applied. This component can be used for shrinking and extending.

Bending (see Figure 22)

This component displays a bending motion. When inflated, the air pouches on either side of the diamond shape continue to grow in their volume, causing a compressive deformation on the diamond-shape seam. Due to the inextensibility of the material, the compression causes the pouches on the side to bend toward each other, thus resulting in a bending motion. It is widely used in inflatable research fields as a hinge component (Ou et al. 2016) (Youn and Shtarbanov 2022).

Surfaces

In this category, components with large surface area are selected. Given existing open-source digital tool developed by Panetta, et al (Panetta et al. 2021), this category theoretically can admit as many organic shape as possible despite the limitations cause by material properties in reality. However, between the tool and the fabrication condition, there still requires tailored adjustments to be made through repetitive trial and error in order to successfully design and fabricate them. Through testing, there tend to have higher possibility for the simulation tool to fail when dealing with more complex shapes. Even with the huge convenience brought by the simulation tool, it is still necessary for designers to have a basic understanding of the mechanisms, machines, and materials. Thus, I selected the following components to be part of the dictionary due to their large coverage, unique mechanism, and guaranteed success in fabrication with given tools that I will talk about in later chapters.



Figure 23 Controllable Aperture

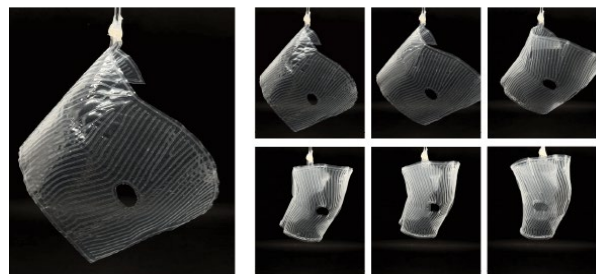


Figure 24 Wrapping

Controllable Aperture (see Figure 23)

This pattern generates a shrinking motion toward the center of the circle. The size of the aperture in the center is controllable by varying the air pressure applied to the component.

This motion can be used for controlling the amount of light, air or liquid coming through the central aperture for shielding or exposing purpose.

Wrapping (see Figure 24)

This surface component (Panetta et al. 2021) demonstrate the wrapping motion that can be used for protective purpose. It forms a quasi-cylindrical volume when actuated. It doesn't have a uniform sectional diameter along the central axis, which gives it flexibility to adapt to organic forms of different plants.

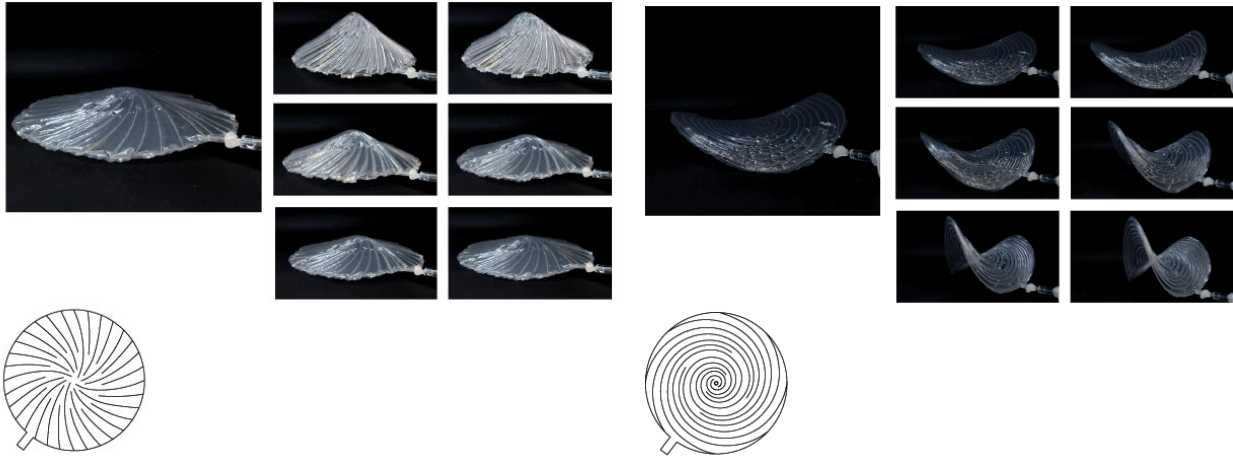


Figure 25 Pinching

Figure 26 Twisting

Pinching (see Figure 25)

This surface component displays a pinching motion when actuated. When connected with joint and curve component, it can form large coverage for sheltering purposes.

Twisting (see Figure 26)

This component displays a twisting behavior of a flat sheet when actuated. This motion can be leveraged for revealing or hiding different information that each side may contain respectively.

Curves

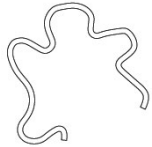


Figure 27 Coiling

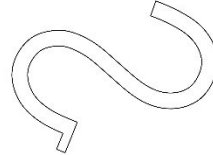


Figure 28 Knotting

Coiling (see Figure 27)

This component (Siéfert et al. 2019) exhibits a curling motion when actuated. Its compliant quality makes it suitable for being used around plants. The curvilinear shape makes it ideal as a structural substrate that can be used for threading surface components and joint components together so as to form assemblies that can transform in multiple dimensions.

Knotting (see Figure 28)

This component exhibits a knotting motion (Siéfert et al. 2019). The knotted structure can create entanglement between the component and plants. The entanglement can be purposefully leveraged for manipulating light-weight plants.

Assembly Examples

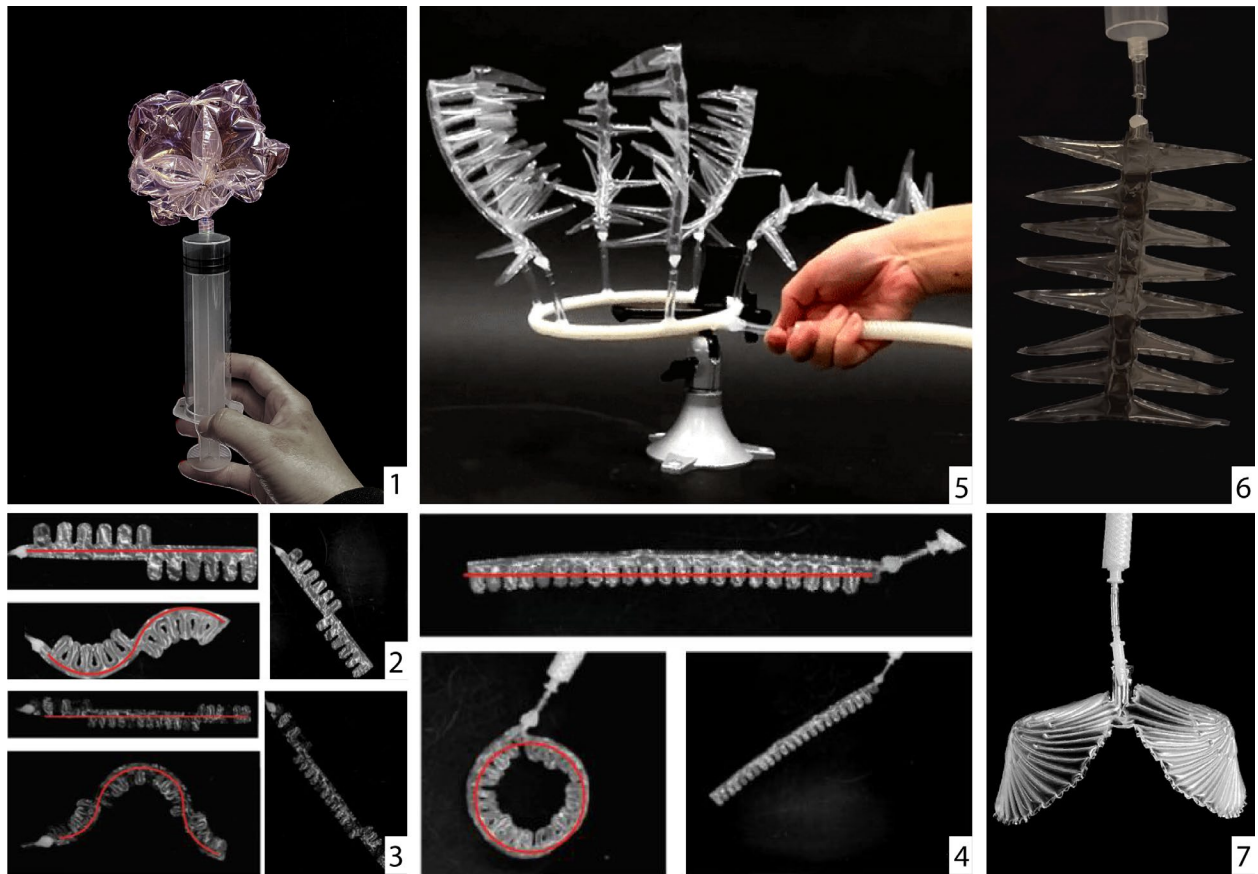


Figure 29 Examples of Assemblies. 1) Rose; 2) 3) 4) Linear elements that bend with different angles through different distributions of finger shapes; 5) Assembly with a 3D-printed holder; 6) Assembly that displays dual furling motion; 7) Assembly that emulates the opening and closing behavior of a shell.

Figure 29 demonstrate a collection of fabricated testing assemblies by combining and organizing different vocabularies together. Those examples demonstrate the versatility of this approach. Although the dictionaries have limited numbers of vocabularies, complex compounded forms and motions still can be achieved by careful design and selection. Instead of being stuck with one patch, the approach to stitch together joints, surfaces and curves allows the assemblies to have multiple degrees of freedom. When supported with external structure, they can even be more empowered to cover or affect larger areas.

Workflow Example

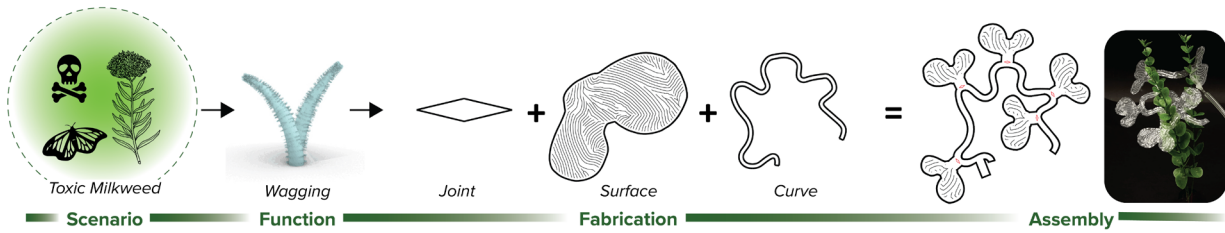


Figure 30 Function to Form Process for Inter-species Communication Prototype

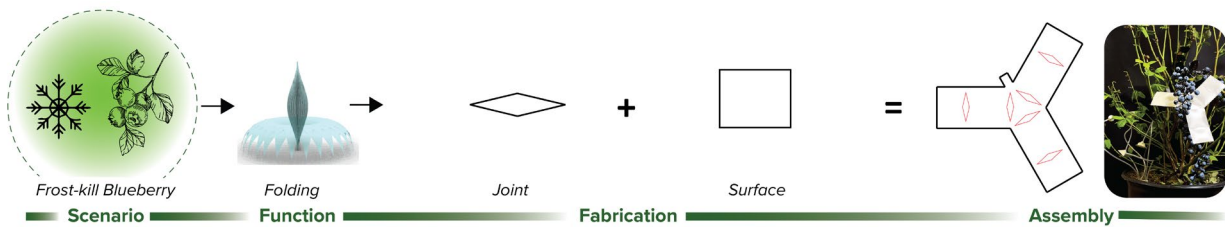


Figure 31 Function to Form Process for Protecting/Sheltering Prototype

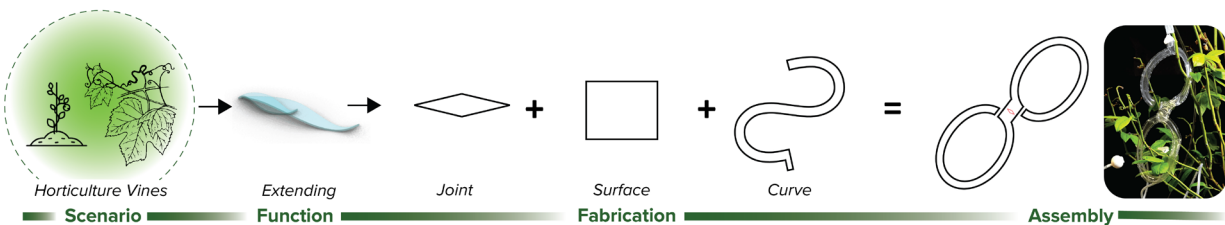


Figure 32 Function to Form Process for Assisting Horticulture/Agriculture Prototype

The process I used to design and engineer the three prototypes as shown in Chapter 3 strictly followed the workflow proposed in this Chapter. Figure 30 – 32 shows this exact process, from context construction to vocabulary selection to compounded form assemblage. This approach helped me to efficiently identify the function and rapidly located fabricable components, and successfully approximated the desired function. It shifts from a semantically rich step to a physical engineering step. This flow helped me to tackle with the underlying complications of design visions and fabrication methods that this thesis works with.

5. Fabrication

This section explains how a combination of CAD (computer-aided-design) tool and vector graphic editor is used for studying, designing patterns for inflatables, and generating G-code for heat-sealing fabrication process. It also explains the fabrication process in terms how to calibrate and control the customized CNC machine and the machine set-up when sealing double-layered sheet materials.

Principal Mechanism

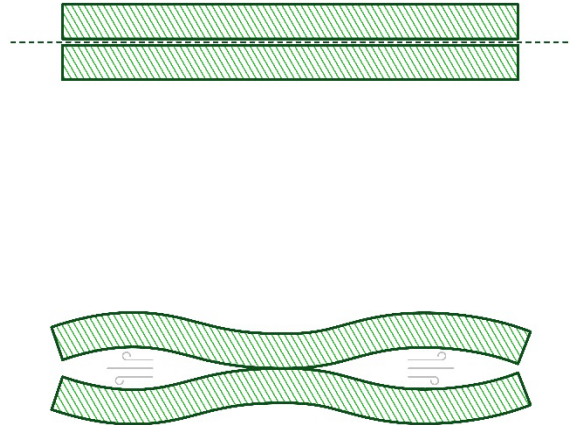


Figure 33 Principal of Inflation with sheet material.

The way how inflatables made of thin and lightweight materials work is as shown in Figure 33. Areas that are not sealed form pouches that will grow in volume when filled with air, water, or other substances. Sealed patterns on the other hand form seams that hinder the air flow and confine air distribution within the pouches. As air pressure increases, deformations are caused due to the inextensibility of the material itself and the compression force the air applies onto the seams. Depending on the geometric relationship between the seams and the pouches, different bending, rotating, buckling angles can be achieved. Based on those principles, different behaviors of the inflatables are studied, and various sealing patterns are designed.

Software

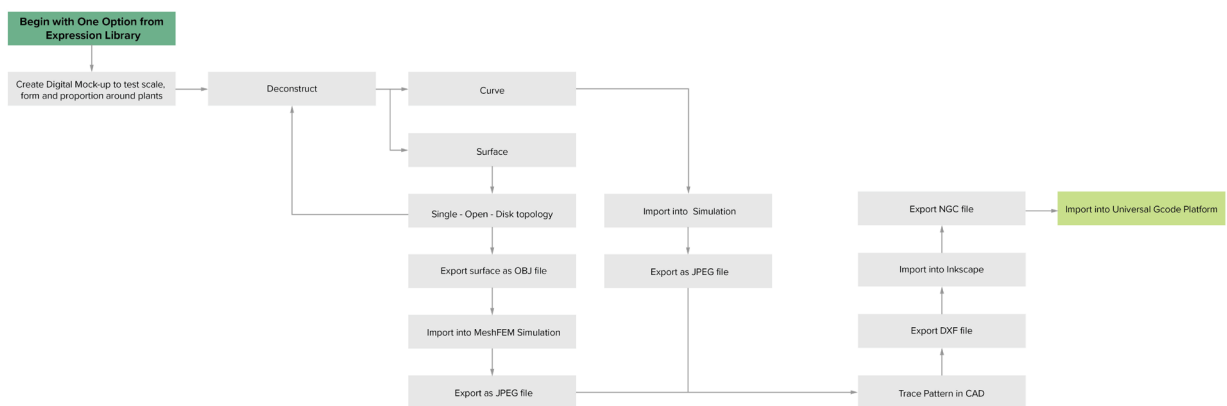


Figure 34 Digital Workflow Breakdown (Larger image see Appendix)

This section explains what software and digital modelling platforms are used for studying, designing patterns for inflatables, and generating G-code for heat-sealing fabrication process (see Figure 34).

Rhinoceros 3D (see Figure 35)

Rhino is used for studying and designing the patterns, joints, and curvatures due to its versatility in creating freeform geometries through the manipulation of curves and surfaces (Stevens and Guy, n.d.). The exports from Rhino are compatible with a long list of other programs. In this thesis, DXF files are exported directly from Rhino to be used in vector graphic editor – Inkscape.

Grasshopper (see Figure 36)

Grasshopper is used for parametrically produce patterns and forms through visual coding (Stevens and Guy, n.d.). It can directly manipulate digital objects in Rhino 3D space in a real-time fashion. In this project, Grasshopper are used for creating vocabularies for Function Library and digital simulations of an integrated system with sensing technology. The motions and reactions of the EPEs can be previewed in Rhino and design decisions can be adjusted efficiently accordingly.

Inkscape (extension included) (see Figure 37)

Inkscape is used for converting DXF files generated by Rhinoceros into G-code using one of its extensions - Gcodetools. In Inkscape, parameters regarding the CNC machine settings are adjusted. The end result from Inkscape is an .NGC file that can be directly imported into the CNC controlling interface.

Universal Gcode Sender (see Figure 38)

UGS(Universal Gcode Sender) is a full featured gcode platform for interfacing with advanced CNC machine. It is mainly used for controlling the head position, path speed, start and stop of the machine in the fabrication process.

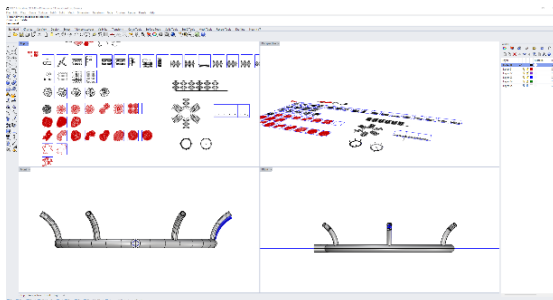


Figure 35 Rhinoceros 3D Screenshots - Work in Progress

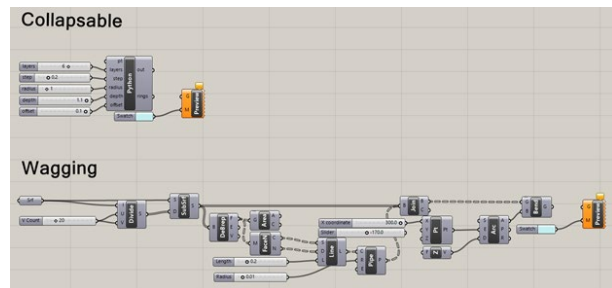


Figure 36 Grasshopper definition screenshots.

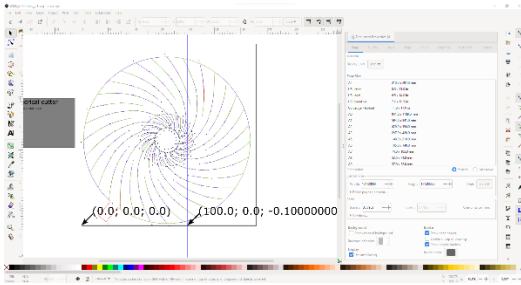


Figure 37 Screenshot of Inkspace Interface

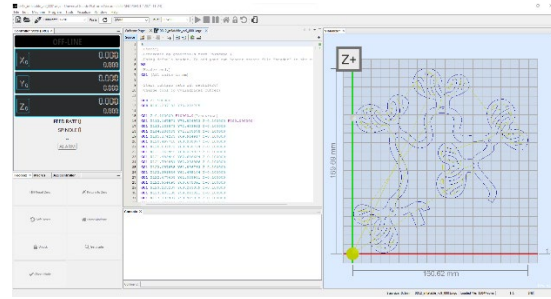


Figure 38 Screenshot of Universal Gcode Sender

MeshFEM/Inflatables (see Figure 39)

It is a codebase developed by Julian Panetta, et al, for their paper *Computational Inverse Design of Surface-based Inflatables* (Panetta et al. 2021). The project uses the code to generate patterns for complicated undeployable surface-based geometries for heat-sealing process. It analyzes any organic surface and generates a network of air channels with which the surface can approximate the target form when actuated.

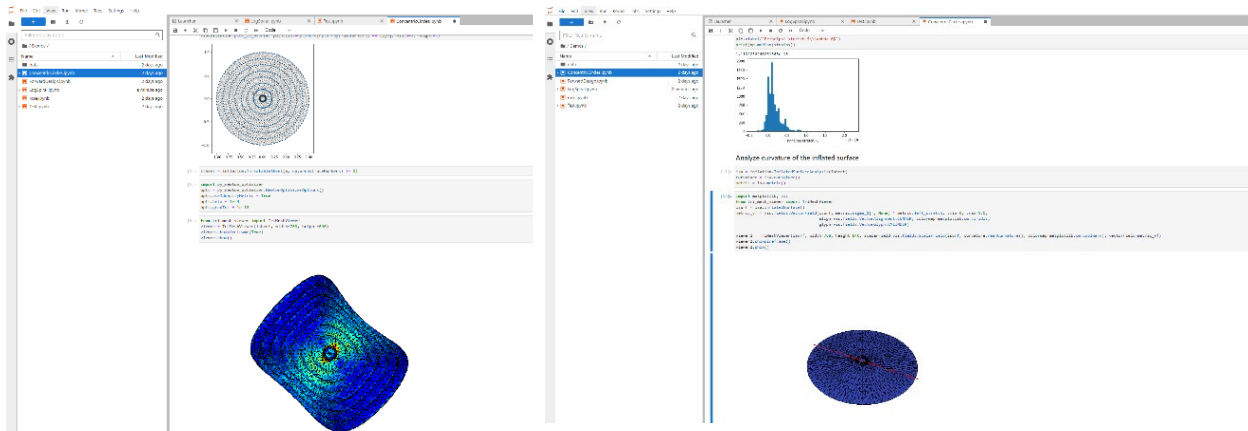


Figure 39 Screenshot of mesh simulation for inflatables.

Hardware and Heat-sealing Process

This section explains what hardware and materials are used for fabricating EPEs.

CNC Machine (see Figure 40)

This thesis uses Zen Tookworks CNC machine as the main fabrication platform. Similar approaches have been adopted by projects such as AeroMorph (Ou et al. 2016), Sticky Actuators (Niiyama et al. 2015). The advantage of using a computer numerical control machine is that it performs better at sealing complex, intricate, and organic patterns when compared to manual sealing. It is more suitable for rapid prototyping as it can directly take computationally designed file with no need of further modification. The workable area for this small footprint CNC machines is 186mm by 201mm. When dealing with dense air channel patterns, the minimal air gap this machine is capable of is 3mm. Anything below this width can cause blockage and lead to undesired results.

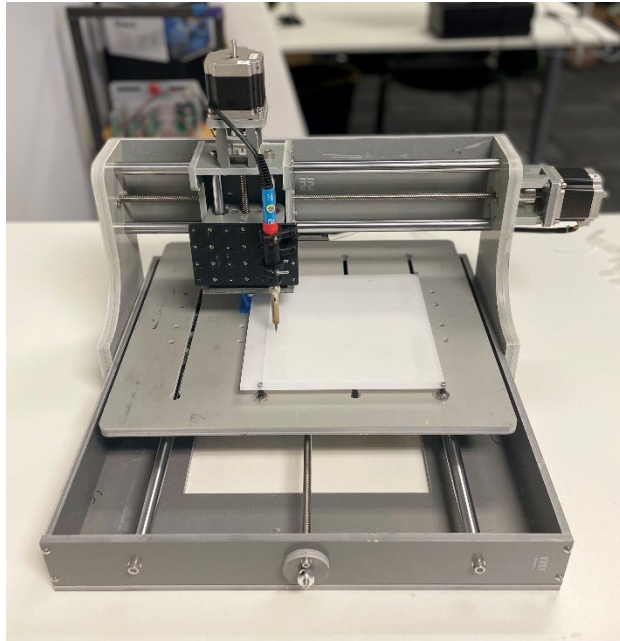


Figure 40 CNC machine with customized attachment.

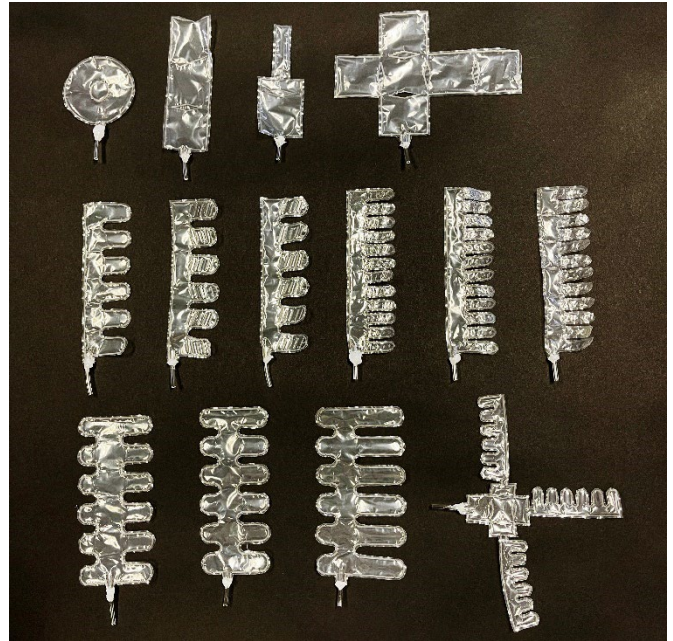


Figure 41 Inflatables fabricated using the CNC machine.

Soldering Iron (see Figure 42)

This project uses FCC RoHS (Restriction of Hazardous Substances) soldering iron for heat-sealing purpose. The temperature used in the process of healing Polyethylene films is 200 Celsius degrees, which is the lowest possible temperature for this specific tool.



Figure 42 Soldering Iron



Figure 43 Polyethylene Film



Figure 44 Teflon Sheets

Sheet Material (see Figure 43)

This project uses ½ mil clear flexible Polyethylene Film as the basic testing materials due to its low cost and wide availability. They are light in weight and have a good air-containing performance in general when heat sealed.

Teflon sheets (see Figure 44)

Two layers of Teflon sheets are used for heat insulation in the heat-sealing process due to the fact that the lowest temperature of the soldering iron is too warm for the plastic film and causes burning or melting without insulation.

6. Discussion and Future Work

In the paper by Guiyi Yi, et al, the authors stated that “cyborgian approach enables designers to take advantages of digital technologies to achieve two objectives: one is to improve the quality of environment by enhancing our understanding of non-human creatures; the other is to encourage a proper level of human participation without disturbing eco-balance.” Those objectives largely align with the design vision of this thesis. And the thesis echoes with the attempt and effort to provide “a possible solution to the concern that technologies are isolating human and nature”. (Yi and Di Carlo 2021)

6.0 Limitations of current prototypes

In order to better understand the limitations of current prototypes, slides of the prototypes were distributed to 8 participants from backgrounds in Human-Computer-Interaction, design, plant science, landscape design, education, and stay-at-home mom (see Table 5). Each slide has explanations in text-form to help participants understand the functionality of the extensions and the scenarios the functions are designed for. The participants were also shown other fabricated geometric primitives apart from the ones being used in the prototypes to further understand the process. The showing of the primitives was also intended to inspire the participants to think of other prototype concepts that could potentially work better according to their knowledge and understanding.

Participant Occupation	Number
PhD Student in Human-Computer-Interaction Design	1
Designer	3
Plant Scientist	1
Landscape Architect	1
Stay-at-home Mom	1
Educator	1

Table 5 Occupation and Number of Participants

The feedback collected from those 8 participants reveals some of the limitations and gaps in the current work that requires future investigation. 1) Limited environmental information being conveyed through EPEs. 2) Functions that center plants more as the subject instead of humans should to be prioritized. 3) Environmental-friendly materials can be used for fabricating EPEs. This can be unfolded in two ways – one is that the material itself does no harm to the environment. For example, bio-degradable or biocompatible materials; the other is that the material can successfully camouflage the EPEs into natural surroundings, causing less to no distractions to humans and animals to avoid the feeling of being surrounded by artificial artifacts when what people want is to enjoy nature. 4) Considering EPEs designed in a way that they can assist and encourage humans to experience their relationship with plants through free and unguided interactions. These gaps and limitations will be partially discussed in the Future Work section and will be considered and evaluated for improvements in the design and engineering of EPEs.

6.1 Application Context

In order to inspect future-oriented application contexts for EPEs, I organize and present my explorative thoughts through a vision mapping (see Figure 46) which constructs a scenario

where humans interact with local plants in a technologically augmented garden. This process helps to ground imaginations and call for a planning of strategic steps to be taken, through which a path that leads to a future of cohabitation is hopefully to be formed collectively.

According to the statistics from National Gardening Association 2021 (see Figure 45), 55% of American households engage in gardening activities. The covid pandemic created 18.3

New Gardeners	Millennials	Generation Z
18.3 Million	65% Increase	44% Increase

Figure 45 Garden Participation (source: <https://gardenpals.com/gardening-statistics/>)

million new gardeners, most of whom are millennials. (“2022 National Gardening Survey” n.d.) Gardens are people’s favorite place to rest and escape from daily routine, as well as a place where they can self-sustain through growing food. It is an intimate relationship between humans, plants and the environment that is established through gardens. Gardens in general not only provide all the benefits that nature provides people, such as enhancing health and well-being, eluding stress and anxieties, etc., but also, different from a wild setting, if privately owned, gardens also provide “opportunities for self-expression, by allowing people to play with the color, form and texture of different plants” (Rodgers, Ploderer, and Brereton 2019); if owned by communities, gardens can support community cohesion as a space for community members to mingle and socialize. In paper *HCI in the Garden*, Rodgers, et al, identified six trends in HCI regarding gardening. They are learning, discovering in the garden, connecting people, coordinating gardeners, bringing gardens inside, and sustainability. (Rodgers, Ploderer, and Brereton 2019) In a recent video essay by Agnes Walton and Kirby Ferguson (Walton and Ferguson 2022), they encourage people to ditch their lawns and start to grow native vegetations and construct eco-friendly gardens around their house. According to their survey, maintaining a manicured lawn not only waste huge amount of water and personal time, as well as causing detrimental damages to the earth and the ecology. Those trends altogether, from both a governmental level and an individual level, point to the choice of having gardens as the initial site for implementing Expressive Phyto-Extensions is a right move to support the ideological transition on a societal level. EPEs are expected to help people revisit, alter, and enhance the relationship between themselves and their plants, and more extensively, the environment and the eco-system.

In order to better depict an overarching vision, I referenced a generic foresight framework proposed by Joseph Voros (Voros 2003) to discuss potential applications of EPEs from a more holistic angle. “The creation of scenarios should come at the end of a careful and detailed process of wide information gathering, careful analysis and critical interpretation. The deeper the interpretation carried out, the potentially more robust the forward views which are created.”(Voros 2001) The graphic (see Figure 46) aims at aiding both the speculation and the design processes through multiple layers that contain different levels

and aspects of information. I am going to break it down and explain the inter-relationships between all the visual components here.

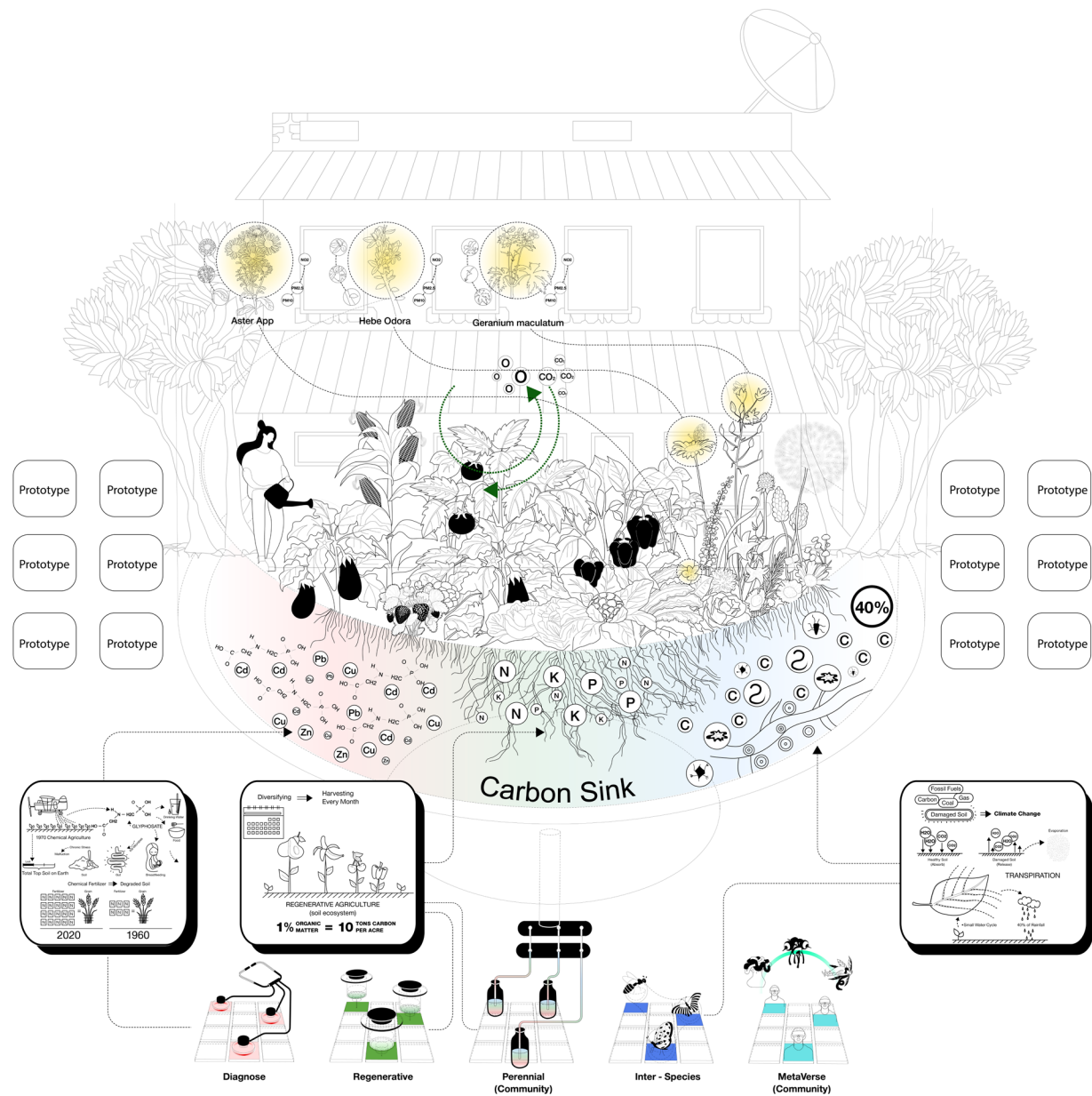


Figure 46 Vision Mapping - Future Application Contexts

Analysis (Historical data and scientific facts - square boxes in the lower part of the figure)

The data and facts were gathered from a variety of sources, including documentary films, expert interviews, national statistics, etc. Those information are put together as “a ‘first cut’ at creating some order out of the bewildering variety of data”(Voros 2003), the first step towards deeper synthetical work. The numbers show how historically the use of commercial pesticides has killed microbes that are essential to soil health and left harmful chemicals that pollute the soil. The lacking in biodiversity causes problems such as desertification, droughts,

soil PH level imbalance, etc. Those results of the analysis are then fed and woven into the second step – Interpretation.

Interpretation (role of a garden on environmental impact and community cohesion - the carbon sink, flower circles and five scenarios at the bottom)

This part is to “seek to ‘probe beneath the surface’ of the analysis to look for deeper structure and insights”. This is the realm that approaches to futures thinking. (Voros 2001) The carbon sink depicts the role of a garden in the environment that can help to store carbon, mediate climate change, enhance soil health. The more biodiversity a garden has, the more environmental and ecological contribution it does. In the top circles, potential hosting plants for the wearables are chosen and analyzed according to their contribution to air quality and soil health. Five different future-oriented application contexts are illustrated at the bottom of the mapping. They propose potential roles the technologically augmented garden could play regarding environment protection and community cohesion. In an alternative future, the garden augmented by the EPEs could become -

- 1) a clinic that diagnoses the environmental problems locally.
- 2) a center that regenerates biodiversity, clean air and healthy soil.
- 3) it can form a network that supports perennial landscape within a neighborhood, given individual garden owner might have specific preference
- 4) it can provide habitats for wild species, way-finding stations for migrating animals.
- 5) if integrated into metauniverse, a garden supported by plant wearable devices, such as EPEs could be associated with virtual worlds, where an interaction between real and virtual could be explored.

Prospection (the Technologically Augmented Garden, Prototypes – the center piece, the small boxes along both sides)

This is the place where an alternative future is being displayed. The prospection part of the vision mapping is concerned with the question – “what might happen?” It is constructed as an informal causal loop diagram forward in time. It illustrates feasible conceptual design of the EPE prototypes and their possible integration with the plants in a garden. A garden that is augmented by those EPEs becomes the ultimate place that an alternative future of cohabitation takes place.

6.2 Future Work

Integration of Artificial Information Processing

As discussed in Chapter 3, I define the Expressive Phyto-Extensions as interfaces that not only help plants to actively respond to their environment but also relay the plant-detectable environmental information to both humans and animals. According to Figure 8, EPEs work in parallel with their hosting plants. While they both reflect biologically mediated information

through shape-changing, the difference is EPEs are expected to deliver more immediate and timely information. In order to achieve that, artificial information processing needs to come into the loop. For future work, state-of-art sensing technologies can be leveraged for translating the biological processed information to digital information. And that information, thereafter, will be displayed through the change of shape, colors, or textures of EPEs and become eligible to humans and animals.

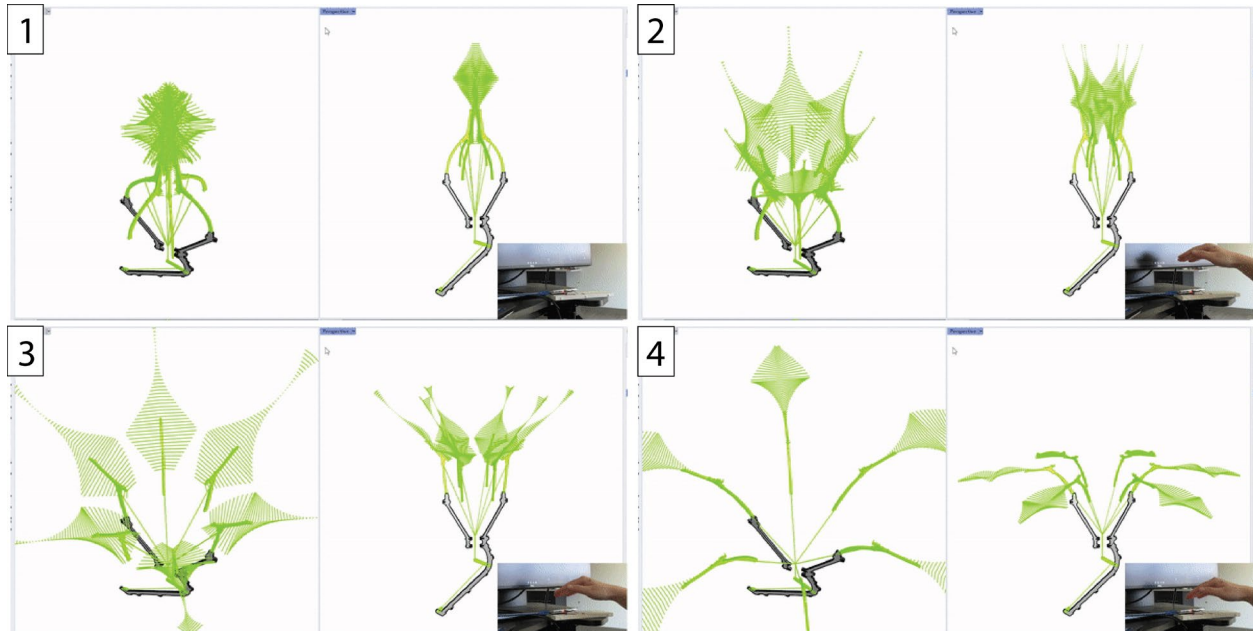


Figure 47 Demonstrating the initial effort of examining how to integrate sensing technologies into the loop. The image shows a digital simulation of how the sensor detects the proximity of humans and trigger the folding gesture of the EPE.

Alternative Actuation Mechanism and Materials

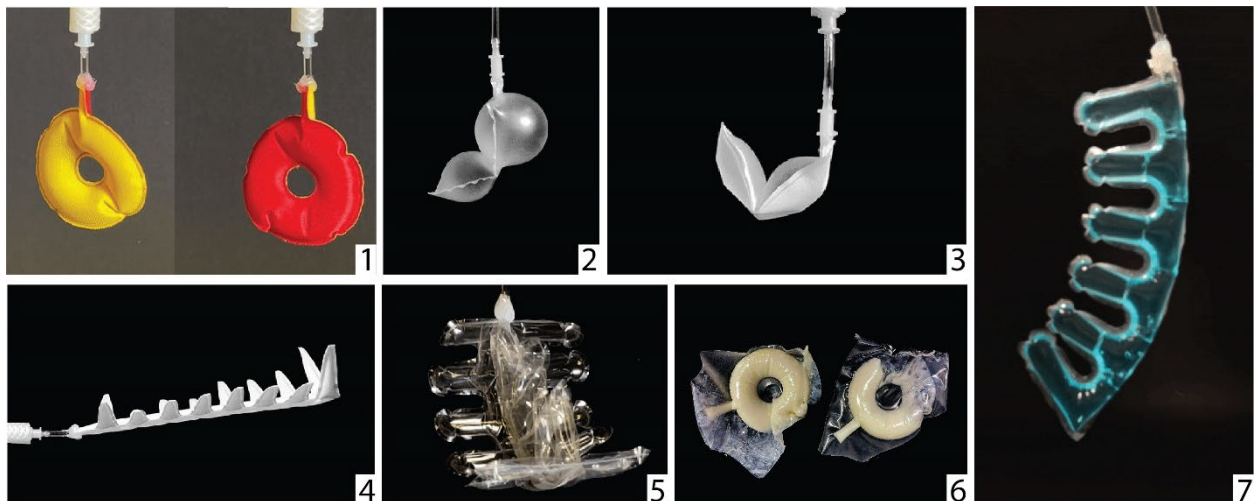


Figure 48 Alternative materials and actuation. 1) Shows an inflatable made of different color on each side. 2) An inflatable made of TPU. 3) 4) Inflatables made of TPU on one side and heat-sealable fabric on the other side. 5) Multiple layers of inflatables are sealed together. 6) Inflatable pouches filled with FlexFoam. 7) An inflatable actuated by colored water.

During the fabrication process, I tested inflatables with different colors, different materials and different actuating mechanism (see Figure 48). Those experiments were irrefutably inspiring and led to much curiosity. For future work, designers can look into integrate those different aspects, such as color, smell, texture, etc., to make EPEs more versatile and capable of more functions. For alternative actuating mechanisms, water can replace air to actuate the inflatables for shape changing purposes. This can be leveraged for different sites where water actuation is more reachable and makes more sense. Another interesting experiment on alternative actuating method is to fill FlexFoam into the pouches. Those expanding materials can turn into permanent structure within the pouches. Their environmental compatibility and functionality can be further studied.

Cyborgian EPEs

Below are some fictional thoughts as fun byproducts of this thesis. I put them out here in case they provoke interesting discussions in the near or far future. Different parts of plants (see Figure 49 and Figure 50) can be examined upon their biological and aesthetic potential to inform the design and engineering of EPEs. Parts with different morphological features such as rhizomes, fast moving leaves, adventitious roots can be considered as inspirations when designing EPEs' forms. While the organ's biological mechanism, modularization type or organizational formation can be used for informing the assembling and transforming logics. Hollow culms, such as bamboos, horsetails, can inspire bio-mimicking structures for encasing external devices. Or flowers, such as dandelions with a unique dispersal system, can be studied as a dis-assembly model. Non-vascular plants, such as moss, can be examined as a form of wrapping or skin system as well.

If technology allows one day, EPEs' are made of a bio-compatible materials synthetically engineered with living plant cells and can keep growing post fabrication. Then, EPEs, with exogenous functionalities that the original plants don't have, can be grafted onto and grown

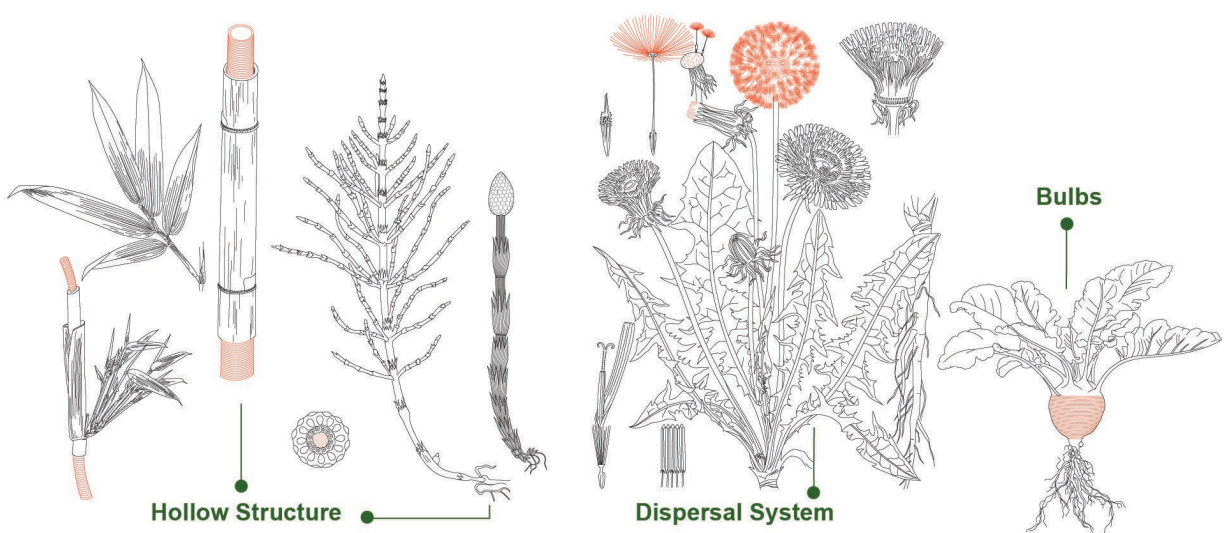


Figure 49 Speculation of utilizing different organs of plants as exogenous functional part of the hosting plant.

into their plant hosts (see Figure 51). They become a living part of the plant that combats environmental challenges.

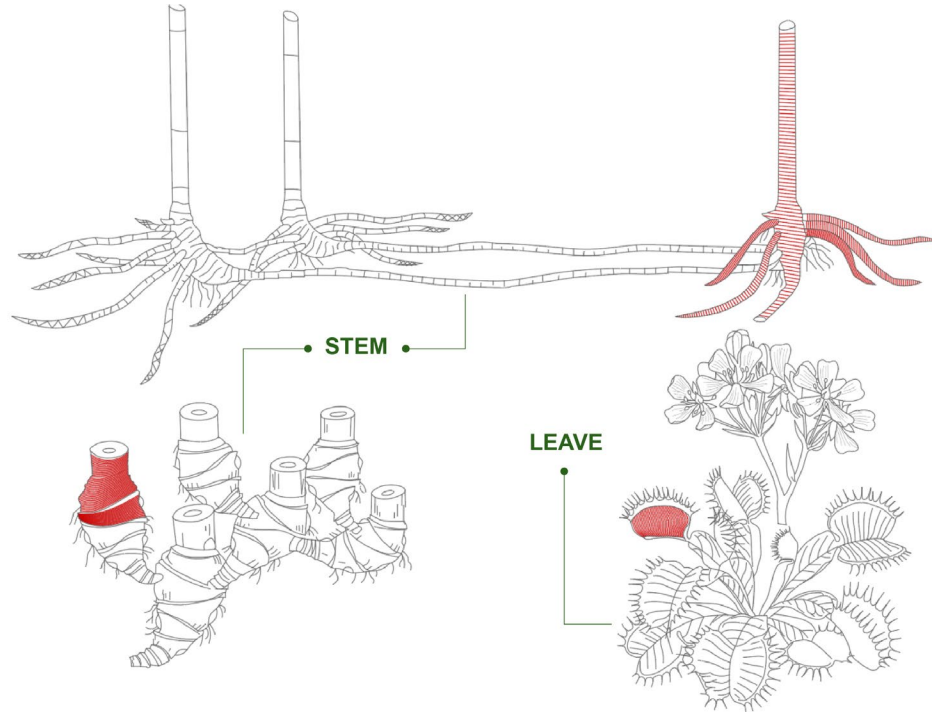


Figure 50 Speculation of utilizing different organs of plants as exogenous functional part of the hosting plant.

Stem/Branch

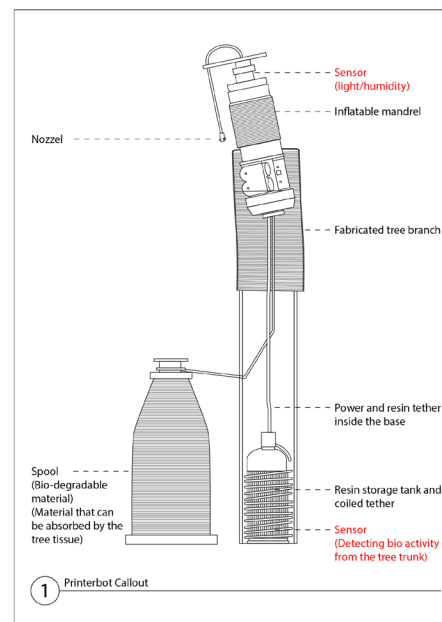
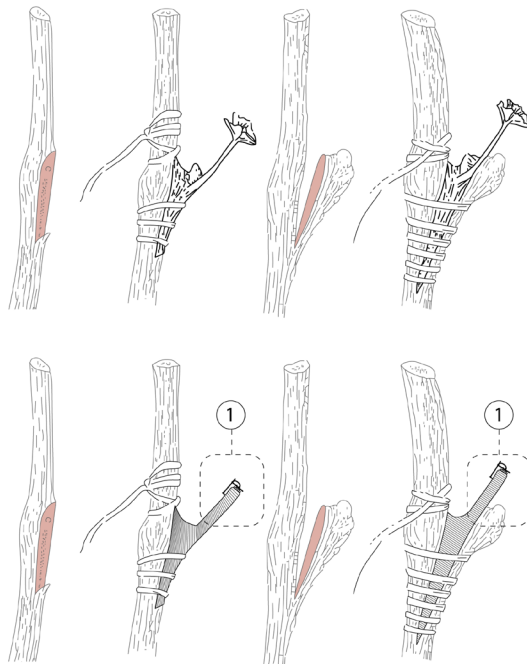


Figure 51 Self-growing Robotic Branch Grafted on Hosting Tree

7. Conclusion

This thesis poses a new function-to-form problem in designing wearable extensions for plants for enhancing the interactions between them, humans and the environment and proposes a provisional workflow that helps designers to narrow down to a concrete scenario, define a specific function and design fabricable assemblies to emulate the function. It provides an Expression Dictionary with carefully selected components that enable designers to rapidly prototype inflatable extensions for plants without requiring much prior knowledge in math or physics.

The goal for the thesis is two-fold. On a vision level, it investigates into the possibility to design interfaces that can help plants to actively respond to environmental and ecological stresses and relay that to humans and animals. The thesis takes on a more-than-human approach and continues the efforts in designing interactions for subjects that are non-human, in which case human designers usually lack first-hand experience. The thesis proposes a context-driven approach with which it leverages domain expertise, in-depth research, and scenario construction to best approximate the needs of plants and their environment. The vision is based on the perception of treating “human-environment” as one organic entity in which the two parties are interchangeable with a blurred boundary. Respectful awareness of our surroundings and non-human living organisms, despite irreconcilable differences, is what this vision seeks to bring about. The designing and engineering of Expression Phyto-Extensions proposed by this thesis pertains to such a vision.

On the fabrication level, the contribution of this thesis is the offering of a dictionary that encompasses fabricable components for people from various backgrounds to experiment

and prototype with inflatables at ease. Though I focus on limited number of components in each category in this thesis, the dictionaries can be expanded with new vocabularies based on rising needs and urges. The thesis proposes a method to configure inflatable assemblies that can approximate certain functions, going beyond known limitations both on material level and form level. I believe this approach might be useful in other inflatable application domains, such as fashion, decoration, etc., especially when people that are new to fabricating inflatables are expected to engage.

Currently, there still exists the gap between the actual utility of the prototypes and the functions they are designed for. In future work, I hope to narrow down and eventually close the gap by integrating Expressive Phyto-Extensions into a more holistic system where plant-detectable environmental information can be truly biologically and computationally mediated for guiding the behaviors of EPEs and passing that over to others. The current functions are limited and could be improved by considering alternative actuating mechanisms, combining extra features with inflatables (including colors, textures, and smells), leveraging sensing technologies, experimenting with materials that have distinct properties (various stiffness or elasticity, etc.).

Appendix A: Interview Transcripts

First Interviewee – Adam Haritan

Background of the Interviewee and how I got connected -

Adam Haritan is a Youtuber that runs a Youtuber Channel called *Learn Your Lan*. (Haritan n.d.) At the same time, he is a regular forager who has great interest in exploring nature. He established the channel to help people know more about their surroundings and other species, as well as share his knowledge and experience. While searching for information from all kinds of resources and media, I discovered his channel. The contents on the channel attracted me as they are highly relevant to the human-plant-nature topic that this research focuses on. I started to follow his channel and watch his videos. Adam happened to be a Pittsburgh local and is familiar with the area. I reached out to him through email, and he accepted my interview invitation. Here are the questions and answers from the interview with Adam Haritan.

Question Lists -

- **Q:** Can you tell me a little bit about yourself? (background, education)
A: I studied Nutrition Science at University of Pittsburgh in year 2014. My background in Nutrition Science made me become interested in a healthy lifestyle. In year 2015, I started my own entrepreneurship. That was when I started exploring foraging and building up knowledge regarding that. Foragers have a group. And I started foraging by following my forager friends. They are a lot of professors who are wild foragers back in my school
- **Q:** What does a wild foraging trip look like? Does the forage happen intentionally, or you forage on the fly as you go out?
A: It is always intentional. I don't have my smart phones with me, no app. I learn about foraging through books and talking to people.
- **Q:** What kind of tools do you use while foraging in the wild if any?
- **A:** For mushroom hunting, I use knife and basket. I usually just pluck with my fingers. Sometimes a small shovel would be helpful.
- **Q:** What are some of the concerns you have regarding foraging?
A: Heavy metal contaminations in soil is always a big problem. The most common polluting chemical here is lead. Those contaminations are leftovers from the coal-mining history. Also, the use of pesticides is another problem. If an apple orchard looks old here, it is mostly probably contaminated. And there is no direct or easy way to know if the food from the land is polluted or not unless you know about the history of the area.
- **Q:** Is wild food better, healthier than those we buy from stores?
A: Some wild food is more nutritious than the food that we usually buy, but some are not as nutritious. For example, clovers, dandelions have bitter compounds. They are

not as tasty, but they are more nutritious. There are wild food instructors that know a lot of the nutrient facts about wild food. Wild species usually have stronger genes than domesticated species because they have to survive under all different kinds of environment. It is like comparing a chihuahua with a wolf when you think of comparing the food we get from store such as kale, broccoli, etc. with wild leaks, dandelions, etc. But also note, wild food may be way more contaminated than food from store depending on where they come from. Some plants are hyper accumulators. Meaning they can be containing more polluting chemicals than others. Usually, food that grow in soil are more contaminated than those from trees. Fun facts are some of the food we get from stores are simply wild by nature and they have never been domesticated. For example, pecans, maple syrup, to name just a few. East and Food Co-op in East Liberty is my to-go place for groceries.

- **Q:** Do the wild species live well in urban landscape? Can we introduce them into an urban context?
A: Urban environment has a different eco system. Wild plants tend to grow better without human intentions.
- **Q:** Where do you usually go for foraging and observation?
A: Foragers don't usually want to give out the spots that they usually go. :D It is illegal to forage in city parks, where they have strict rules. State parks are better places. I usually go to Allegheny National Forest. (<https://www.fs.usda.gov/allegheny>) Mushrooms, berries, fruits... you can find a lot of these there.

Second Interviewee – Hanna Mosca

Background of the Interviewee and how I got connected -

Hanna is the Garden Dreams Greenhouse and Farm Manager, overseeing agricultural production and apprentices at the two sites. (<https://www.growpittsburgh.org/about-us/staff-and-board/hanna/>) I got in touch with Hanna during an open house held by Grow Pittsburgh, which is a local organization in Pittsburgh. Grow Pittsburgh's mission is to teach people how to grow food and promote the benefits gardens bring to our neighborhoods. They are committed to addressing any local or statewide policy hurdles that interfere with the success of urban agriculture in the region. (<https://www.growpittsburgh.org/advocate-for-urban-gardens/>)

Question Lists –

- **Q:** What is urban farming? How is it different from conventional farming?
A: Urban farming is growing food inside city settings. The lot size of urban farming usually ranges from a quarter acre to one full acre. Compared to gardens, there is monetary transactions that happen on urban farming lot. When growing food on an urban site, we usually want to maximize the amount of food produce given the limited size of lot and try to feed as many people as

possible. The difference is really just about the space compared to conventional farming. Urban farms have smaller size. The way how people grow things change extremely. Growers mostly use hand tools instead of tractors to create beds, for example. Urban farms have much more direct connections with community. Imagine having a farm that is one block away versus miles away. They also help to create more green spaces within the city, promoting diversity in urban landscape.

- **Q:** Can you talk a little bit more about how people grow on urban farms?

A: We usually use succession planting and grow multiple plants on one piece of land. We also grow different species in spring and fall. We try to grow as much as we can within short seasons, limited space by splitting beds. We are constantly thinking about what is the next thing that should go into the bed. It is something that is always on my mind.

- **Q:** How do you pick sites at Grow Pittsburgh for urban farming? What are the considerations?

A: We have several sites at Grow Pittsburgh. There are Braddock Farms, Frick Greenhouse, Garden Dreams and Shiloh Farms. They all come from different sources. For example. The Garden Dreams used to be a privately owned nursery by Mindy Schwartz, who is the co-founder of Grow Pittsburgh. Shiloh Farms was a lot donated by two gentlemen who now live next to the lot. There used to be a house on that lot, but it was burnt down by a fire long time ago and now it is converted to an urban farm that serves the community. When choosing sites, we consider sun exposure, water access, facilities access, such as shed, etc.

- **Q:** What are some of the challenges when growing in an urban context?

A: The urban soil has a high PH level. It is almost always above seven. So we have to amend the soil with sulfur. However, the soil PH level can also be changed by growing plants such as blueberries. They can make the soil acidic. Another challenge is soil contamination. For example, the site, where Braddock Farms now is sitting on, used to be a steel mill. The lead level is extremely high, which requires frequent soil test. We test the soil quality every year. In terms of pest control, we use neem oil spray for our farms instead of conventional pesticides that leave toxicants in the soil. Neem oil spray won't harm beneficial wildlife, such as pollinators. We also control pests by using insect netting, setting up physical barriers. Our workers also hand pick bugs. In order to make sure our vegetables are healthy food source to our communities; we test lead level on vegetables and compare the level difference on washed vegetables and not washed vegetables. We found out that washing vegetables can make the lead level go down. Air pollution in the city could also contaminate the food on urban farms. And there is a lot of chlorine in city water. That is something to be concerned about as well.

- **Q:** How does soiling text look like?

A: We send soil samples for testing three times every year. Each time it costs around \$100. It is a very complicated process to get soil samples in order to have an accurate evaluation. It is the nuttiest test.

- **Q:** What is the benefit of having urban farms in our cities?

A: When we plant different species on the farm, they help to keep the soil in place. Urban soil usually has a lot of clay. It takes time to build good soil. Urban farms help with maintaining different nutrients in the soil. Plants help to remediate the land. Animals that we raise on the farm, such as chickens, help with keeping the soil healthy too.

- **Q:** How do you interact with the community? How does the farm serve the community?

A: We have a lot of community garden projects, where we have the community members identify their needs. The farms are taken care of by full-time employees and knowledgeable volunteers. The full-time staff spend around 30 hours every week on the farm. When the produces are ripe, it only requires two full days for us to harvest, pack, put together and distribute the food to local residents.

- **Q:** Do you let local residents harvest the produce themselves?

A: We don't have local residents do it. Because they usually don't have proper harvesting techniques. For example, we need to know how much to harvest from each green, not to cut too low, make sure leave the vegetables with the land when they are still harvestable.

- **Q:** What are some of the tools that you use when working on the urban farms?

A: The common ones – shovels, rakes, trowels. We also use knives, clippers, and scissors.

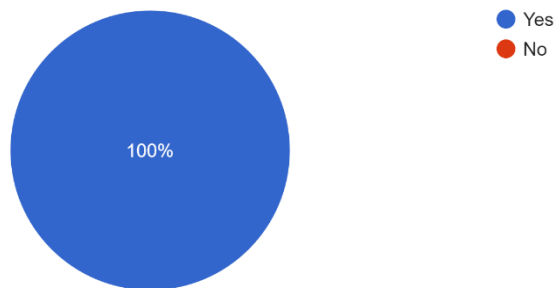
- **Q:** What are some of the technologies you would to be developed for urban growers and you think might be most useful to you?

A: We currently have solar panels at our Braddock spot. The system that we use is in general simple. If there are tools that can help us to understand the nutrient level, contamination level of our produce, that will be really helpful

Appendix B: Prototype Evaluation

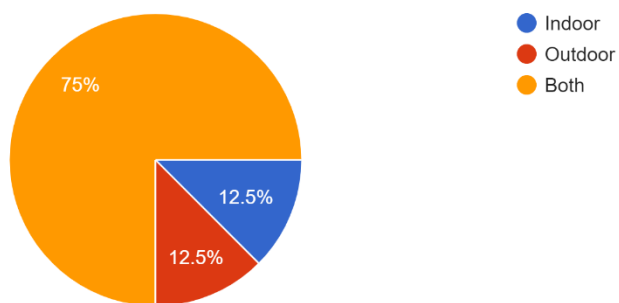
1. Do you own plants?

8 responses



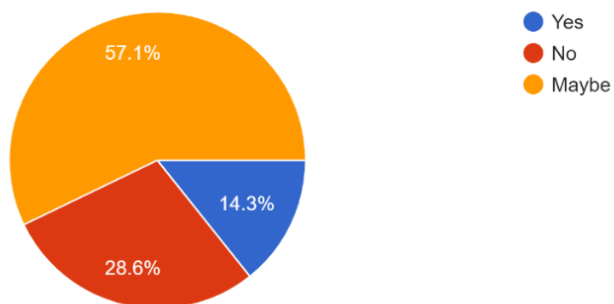
2. Where are your plants? Indoor or outdoor?

8 responses



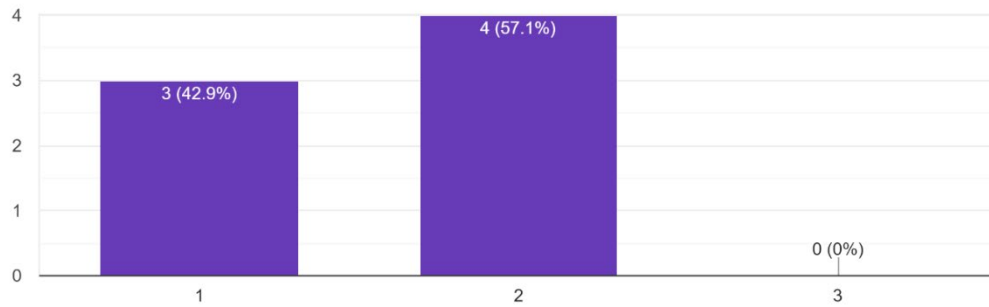
5. Do you think tangible interfaces such as Expressive Phyto-Prostheses (EPP) may increase the time you interact with the plants?

7 responses



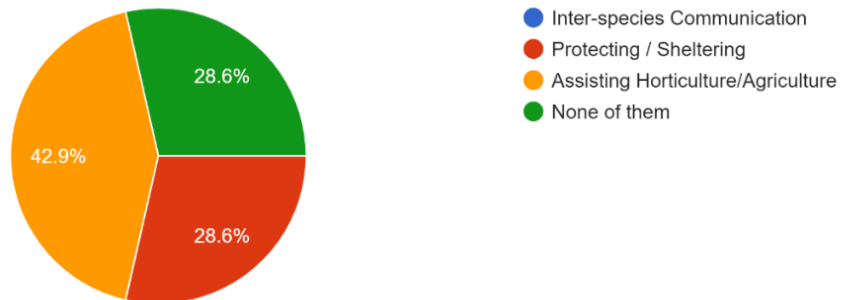
6. If EPP's are situated outdoor, how likely you think the EPP will increase the chance of you spending more time outdoor?

7 responses



7. Which prototype you think makes the most sense and you would mostly like to use/have?

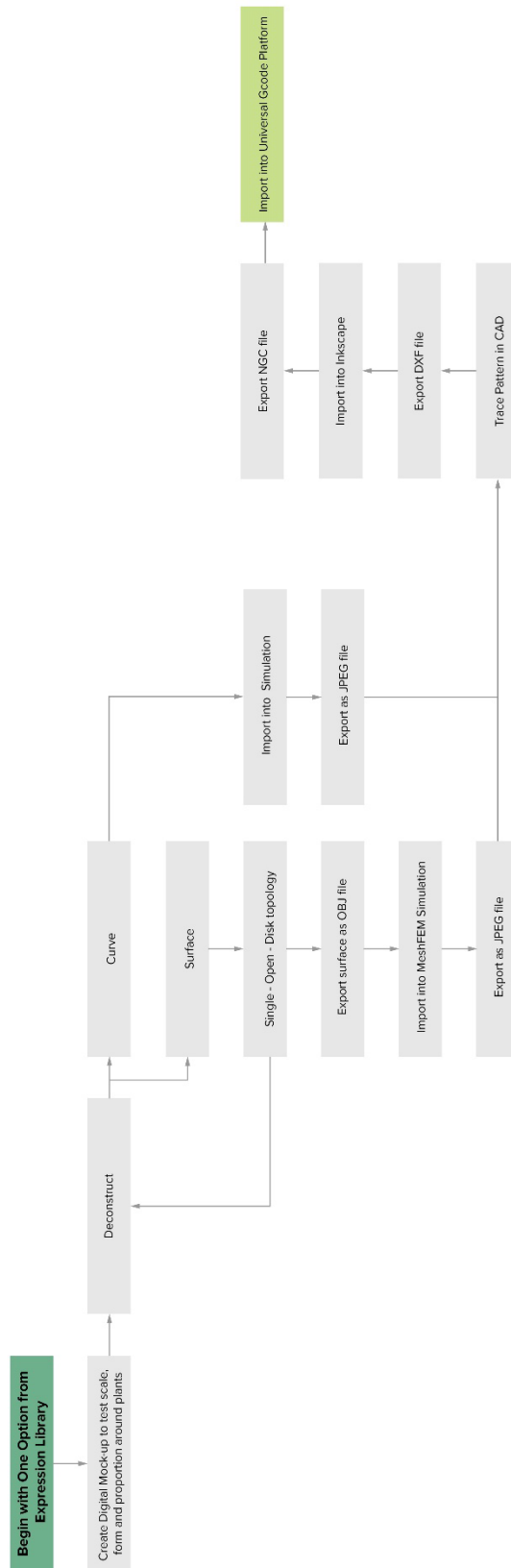
7 responses



0. What is your occupation?	1. Do you own plants?	2. Where are your plants? Indoor or outdoor?	3. How do you interact with your plants? And what is the purpose of you owning plants? (relaxing, food, purifying air, etc)	4. What are some of the challenges for you while interacting/taking care of your plants?	5. Do you think tangible interfaces such as Expressive Phyto-Extensions (EPEs) may increase the time you interact with the plants?	6. If EPEs are situated outdoor, how likely you think the EPEs will increase the chance of you spending more time outdoor?	7. Which prototype you think makes the most sense and you would mostly like to use/have?
PhD student in Human-Computer interaction and design	Yes	Both	Relaxation, enjoyment, sustainable food, tasty food, research interest, aesthetics	Caring for the plants while I am away. Understanding soil health	Yes	2	Protecting / Sheltering
Designer, Design Leader, Curious human	Yes	Both	to care for them and learn from them	i am still learning about how best to care for them	Maybe	1	None of them
environmentally conscious (product) design	Yes	Both	Indoor plants I have to feel more cosy at home and more connected with nature since we live in the city. And during spring/summer I have herbs at the balcony for cooking (them I grow from seeds).	Most of the plant I have needs watering only once a week and once a month I usually clean dust from the leafs (with water and lemon) or give them shower during summer. But this is just nice and calm routine. Sometimes i had pest on some of the plants and that was really a struggle.	Maybe	2	Protecting / Sheltering
Plant Scientist	Yes	Both	i look at my plants and I admire their structures. I also take care of them so I can admire them.	When they are difficult to care for.	No	1	None of them
Landscape Architect	Yes	Both	take care for all of them in general, have a dream for gardening	dry summer right now, needs a lot hand watering	Maybe	2	Assisting Horticulture/Agriculture
stay-at-home-mom	Yes	Outdoor	I do basic pruning, sweeping and mowing. I enjoyed my plants provide me the scenery, privacy and shading.	They grow too fast in the summer. I need to spend a lot of time in maintenance.	No	1	Assisting Horticulture/Agriculture
Designer	Yes	Indoor	I grew up in a very close contact with plants, both indoor plants, gardens, and forests. I feel an inseparable kinship with plants, and I feel like we take care of each other in that relationship.	I generally worry about moving away and having to leave them behind. I also sometimes alienate myself from the reciprocity of our relationship. I am usually able to understand the forms of care I can experience in that it, but I can be either too self-involved or anthropomorphize them.	Maybe	2	Assisting Horticulture/Agriculture
Educator	Yes	Both	I enjoy growing trees. I start them from seeds I harvest and I enjoy watching them grow. Usually, I give the young seedlings away as gifts.	Because I rent a small home, I do not have the space to plant the trees that I grow. Therefore, I give them away.	Maybe	1	Assisting Horticulture/Agriculture

8. Based on your choice for the previous question, briefly talk about why do you like it and what are some of the concerns or questions you have for the prototype? (you may also talk about other prototypes)	9. Do you think EPEs should have a more functional, aesthetics or entertaining role? If other, please explain.	10. If functional, what do you wish EPEs can tell you about the plants or what kind of (environmental) information you wish you can infer from EPEs ?
It seems like a straight forward use-case and immediately usable. However all uses seem valuable.	All of the above. Arguably, sustainable design should be all three.	It would be nice if it could represent the bio-electric signals within plants (see e.g https://www.growingcodesign.com)
the way "environment" is defined on slide 3 feels very anthropocentric. it is my experience that ecological systems also intervene on us. it is a bi-directional relationship. nature knows how to care for itself and i am concerned about the positioning in these prototypes.	as above, i'm struggling with the hubris in thinking that plants need "assistance" from human-created methods. on the other hand, since we've degraded earths living systems so much i do acknowledge we need remediation such as microbes that eat toxic waste, as an example.	whether the EPP has benefit from the plants POV
If we add something artificial, growing and surrounding myself with plants loses its meaning for me. But if there will be something visually inconspicuous that will help me with communication with the plant, it is certainly an advantage.	functional – I see a potential in plant/farm protecting from bad weather conditions.	I meant functional in matter of taking care and protecting plants but in the matter of learning something more about how they feel then it will be really helpful to know if they for example need more water, need to be more in the shadow...
plants don't need help. humans consistently impose their standards and desires onto everything without thinking about other organisms.	entertaining because plants don't need our help.	not functional
the prototypes look very interesting themselves, but I am still having a hard time imaging how this could be applied to a larger horticultural level. Please study further and make it more clear!	I think either super entertaining or super functional on a large scale could both be more beneficial	moisture monitoring and automated irrigation is the hot topic in my plant life this summer for sure, so any relief on that part in the long future is greatly appreciated!
I like the EPP which can assist horticulture. Ideally, in my mind, I think it can decrease my time doing maintenance garden work. I would imagine it can help my plants growing in the right direction so that I don't need to prune so much.	More functional will be good. If it can automatically collect falling leaves or spray/ inject fertilizers, that will be very helpful.	It will be good to tell me what kind of the nutrition elements are lacking for the specific plant. It will also be good to tell me the humidity, temperature, texture and component of the soil.
I don't feel like I know enough about each of the "issues" that these prototypes are addressing, which makes me regard them as a bit redundant. I like the aesthetic, and I enjoy the perceived interaction between the prototype, the plant and their environment, but I would definitely love to know more	Again, I do not fully understand the necessity for their functions, but I enjoy the aesthetic and entertaining aspects.	I am not sure what kind of human-plant mediation would be necessary. My instinct is to allow the human to experience their relationship to this plant through free and unguided interaction, instead of a more interface-based interaction.
Because plants that are reared in horticultural/agricultural settings are typically weaker than their wild counterparts, I can imagine that in some settings EPPs would be useful to provide assistance that humans cannot provide.	I think the most important role is functional. If they are used in horticultural/agricultural settings, functionality seems to be the most important role. If, however, EPPs are sold commercially to household users, I could see a need for aesthetics and entertainment.	Because I am a forager, I would benefit by knowing if the plants have acquired any kind of toxic overload that would be detrimental to my health.

Appendix C: Digital Modelling Workflow



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