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Master thesis

How can sensing techniques redefine our interaction with plants ?

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1 Introduction

1.1 Background motivation

I am an creative technology engineer that is passionate about embedded systems and their hardware/software architecture. Pushed by my principal investigator and motivated by challenges, I wanted to explore the intersection of biology and electronics. I aim to transform plants into bio-sensors, using their natural sensing capabilities to capture the human-plant interaction. Extending the capacities of a single plant, I want to create a network of plant-based sensors.

I am also interested in the use of sensor data. With no particular appetence for musical creation, my principal investigator challenged me onto create a device that can use the data from the plant and generate sound based on interaction. The musical generation allows the plant to be listened to and to care about it.

1.2 Context and overview

This research is in line with the new means of interaction and new sensors that surround us every day. This master's thesis seeks to use the natural capacities of plants, which are made up of thousands of sensors, and to understand them. This could make it possible to create plant networks and monitor the state of our green partners. At the same time, it could reduce the amount of silicon needed to deploy a sensor field. It could also open up new possibilities in the field of Human Computer Interface research by adding a new interface.

1.3 Problematic

The main problematic that this master thesis will focus on is :

How can sensing technologies redefine our interactions with plants ?

1.4 Research domain

Research domains on the human-plant interaction are wide. The HCI* field is focused during this master thesis. The Human Computer Interaction field focuses on the interfaces between people and computers. This field is at the intersection "between psychology and social sciences, on the one hand, and computer science and technology, on the other" [1]. This master thesis aims to work onto the interaction we have with plants and nature and to enhance plant capabilities.

The plant is transformed is used as a living sensor and thus the project is reaching the instrumentation engineering and electronic field. This field aims to think and create new way of capturing data to make sensors. A bio-living sensor such as the plant needs to be understood using sensing techniques.

The sensor making and creation field is also focused. In this master thesis plants are transformed into sensor. This transformation...

* Human Computer Interaction

1.5 Contributions

2 State of the art

2.1 Plant as sensor

2.1.1 Human-Plant cohabitation

Plants have a lot of benefic effects on human. The study from Charles Hall and Melinda Knuth [2] explain all the benefits of plants on our human system. Watts and al. shows that urban "greening" (add green spaces in urban city) increase tranquility, relieve stress and anxiety [3]. An experience has been conducted in offices by Ikei and al [4] to expose roses to employees. The experience showed that the "parasympathetic nervous activity was significantly higher while viewing the rose". The subjects were more comfortable being expose to roses than people that were not.

2.1.2 Human-Plant interaction

The human plant interaction has been studied. Seow and al. [5] created a framework that is able to detect when something (and someone) interact with a plant. However, this is not any plant, the plant used is the *Mimosa Pudica*. This plant is special, when something touches its leaves, the plant closes its leaves to protect them from the danger [6]. An electrical impulse is released and is catch by the device Seow and al. developed. The electrical signal is easy to catch and thus can be used as actuator. However, the plant needs time and energy to re-open the leaves. This framework also can't be generalized to other species of plants.

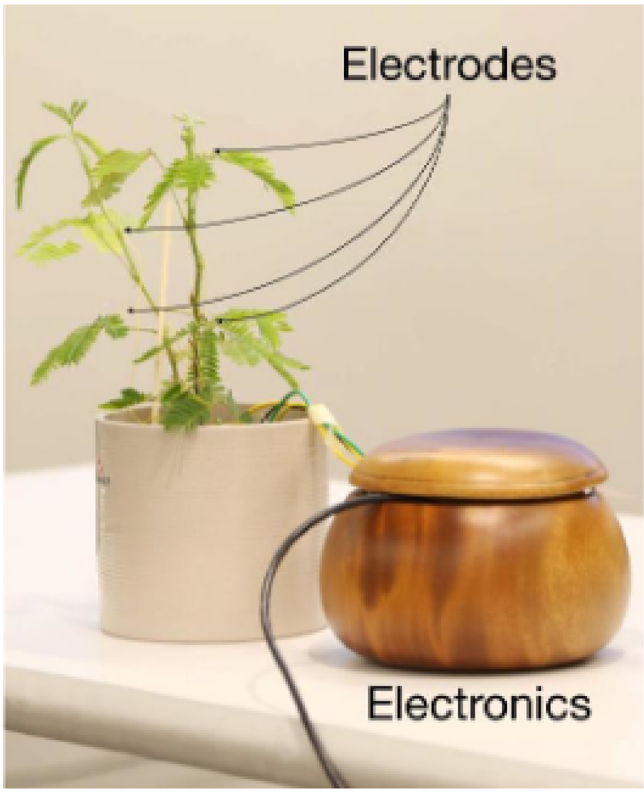

Figure 1: *Pudica framework* made by Seow and al. The *Mimosa Pudica* is a special plant that react to the interaction by closing its leaves. The framework captures the electrical impulse and then interprets that an interaction happened.

Sato and al. used the process of capacitive sensing to detect interaction with objects of our daily lives [7]. In this paper, they proposed a device called *Touché* that use swept frequency capacitive sensing to detect touch interaction but also more complex interactions (such as interacting with a finger, the whole hand...). More complex interactions are captured using machine learning algorithm.

This paper doesn't apply the device to plants. Poupyrev and al. [8] used the device on plant to demonstrate the usage. This swept frequency technique is usable and better than the previous single frequency technique as it captures more data. In their article, Honigman and al. [9] adapted the *Touché* device to be use with an Arduino[†] microcontroller. This allowing people to reproduce the set-up easily.

2.1.3 Plant as sensors Plant transformed into sensors

2.1.4 Touch sensors

Usual sensors uses physical properties to capture the data. For instance, in 1999, Hinckley and al. [10] were building a touch sensor made of conductive paint. The conductive paint is used as an electrode. In the circuit, a component is generating a 30 Hertz square signal. When the user interact with the conductive surface, it shifts and induce delay in the square wave. The delay induce by the user hands is caused by its natural capacitance. This circuit, however, gives a boolean output based on a threshold. The answer is *touched* or *untouched*.

When thinking of touch sensors, we think about the trackpad/touchpad that we daily use in our personal computer. Those sensors use resistive or capacitive sensing. Both of these techniques are based on electrical properties. Resistive sensing is based on the perturbation of the resistance in a circuit. Whereas capacitive is based on the capacitance. Capturing those specific properties are usually the basic of touch sensors.

For instance, Olberding and al. created a cuttable multitouch sensor based on capacitive sensor [11]. This specific sensor allows to create something similar to a trackpad but with different shapes.

Reading the capacitance at a fixed frequency is working and is already used in our daily lives. However, to capture more complex interaction and to rely on the data, adding another dimension of data is useful. Swept Frequency Capacitive sensing consists on emitting a electrical signal and then read the capacitive values similar to what a classic sensor would do. However, the electrical signal is not generated at a fix frequency but is generated following a changing frequency. Sato and al. introduced first this technique in the touché device [7]. This allows to get richer information on the output of the device. *Touché* allows then to capture the information on a variety and a multitude of daily objects. Indeed, searching through many frequencies make it simpler to find small changes and though different kind and type of interactions.

2.1.5 Sonification

Sonification is "the use of non-speech audio to convey information or perceptualize data" [12].

[†] Open source compute unit

The sonification has been used for a long time using the human ear sensor to interpret data. For instance, the Geiger counter is using the sonification to measure the ionizing radiation. This sensor is "beeping" and "crackling" depending of the level of radiation.

Herman and al [12] created two sonification models to represent particles moving. They are saying that the sonification is allowing a multidimensional representation of the data captured. Humans are sensible to sounds. The sound allows a "rapid screening" because it is easier to listen to a sound than read a graph or a text. The sound when combined with visualization is bringing more granularity and understanding. They are also adding that we are using sound to diagnosis issues on a daily basis ; giving the example of a car mechanic that is having a failure and that we can predict.

The sonification has been used in many projects. Ballora and al. [13] designed a project that mix the fluctuation of the stock market with the apparition of keyword on Twitter social network. They were mapping specific and defined keyword with specific sounds. The designed an app to be able to tweak and change the volume of the different sounds. The same procedure is applied to the variation of the stock price. They conducted this experiment in order to add another possible channel of information in the market place. The traders and people working there are already flooded with visual information. This new channel could allow to process more data. The result were encouraging. However, this experiment rose issues. People were annoyed and disturbed by the sound. They were lowering the volume and thus not hearing it. Some other people were just too much concentrated on their task that they did not hear the variations. More experiment should be conducted to refine the sound created and the level needed.

In the same direction, Ballora and al. [13] also developed a device to monitor the heart rate of people using sonification. It takes the output of an electrocardiogram and transform it into a sound. Each of the ECG's frequencies were pass into a filter and then given a specific sound. The output of the sound creation is then listened to and interpreted. This application with a trained ear can help diagnosis the sleep apnea through heart variability.

2.1.6 Sonification on microcontrollers

MCUs[‡] [14] is a kind of small computer. Those devices can be used to generate sound. The most common way of doing electronical music is to use MIDI[§] [15]. MIDI has been created in order to create music with digital computer. MIDI do not describe directly the audio signal but the human actions to create the signal (such as turn the knob left, push the slider...). MCU are able to produce those kind of directives [16][17]. However, the MCU can produce MIDI but MIDI does not directly generate sounds. A synthetizer is needed to create the sound described.

For our use case of embedding the device, we look at MCU that were able to directly generate the signal from a DAC[¶]. Projects had been conducted

[‡] microcontrollers
[§] Musical Instrument Digital Interface
[¶] Digital to Analog Converter

with many microcontrollers such as a small 8 bits AVR microcontrollers (ATmega32) [18]. This paper does not include limitation of such a product but we can guess that the 8 bits microcontroller is limiting the sound quality. A larger project from Shaer and al. [19] is including an Arduino Mega controlling the visual effect of the project, but also the interaction sensors. The Arduino Mega is then sending MIDI information to Teensy 3.2. The Teensy is then generating the sound. The project is still too large to be fully embedded but the Teensy 3.2 is a promising compute unit. The Teensy 3.2 is running at 72 MHz, way faster than the ATmega32 that is operating at 16MHz. The frequency is essential when trying the produce sound signals.

2.1.7 Commercial products

Generating music from plants is not a new concept. Several commercial products are available on the market. Looking at *PlantWave* device from the eponym company, the device is able to generate sound from the plant. The device is built using a small box with two electrodes. The electrodes are then connected to the plant. The device generates sound. The process of sonification is not described and thus is blurry as it is a patent technology. The device is also not open-source

Figure 2: The PlantWave product on a demonstration picture (source from their website)

Another commercial product is the *Music of the Plants* product. How the product works is even more opaque and the company building the product is sometimes associated with cult and esotericism. The product is also not open-source.

2.2 Internet of Plants

The Internet of Plants in not a new word. Nevertheless, the term is not that spread around. Aliev and al. [20] evoked the word. The paper explain that the word is based on the IoT. The paper is using this word to describe a system of sensors to monitor plants and crops. This is really close to

Internet of Things

the IoT as it is using silicon made sensor to retrieve the data from the plants.

Internet of Plants is especially used for agriculture. In the paper of Steeneken and al. [21], they are explaining that the use of specific sensors could and should be very efficient to boost the productivity of the crops. The paper is also using talking about classic connected sensors but applied to plants.

Like the previous authors, Kitano and al. [22] also used this specific word for sensor connected agriculture. I think that the IoP of plants in that use is more a specific application of the IoT instead of a specific field of research.

2.2.1 Distributed instruments

2.2.2 Sonification using software

3 Plant as sensor

3.1 The electronic interface

The electronic interface is the interface that allows a compute unit to capture and interpret the plant signal and communication. The interface is a device made by us for this use case. The printed circuit board (PCB) device is composed of 3 main parts:

- The core of the circuit, the microcontroller, an ESP32 Wroom 32
- An electronic filter connected using an electrode to the plant
- A sound part of the PCB that is including an audio amplifier, a volume knob and a terminal block to connect a speaker

The design of the PCB has been done using the open source software Kicad. As said previously, the circuit contain 3 parts.

The core of the circuit is the computation part, including the microcontroller, an ESP32. All the other devices of the circuit are connected to the ESP32. The choice to use a devkit has been done to ease the electronic conception and to avoid any communication and soldering issue with the MCU*.

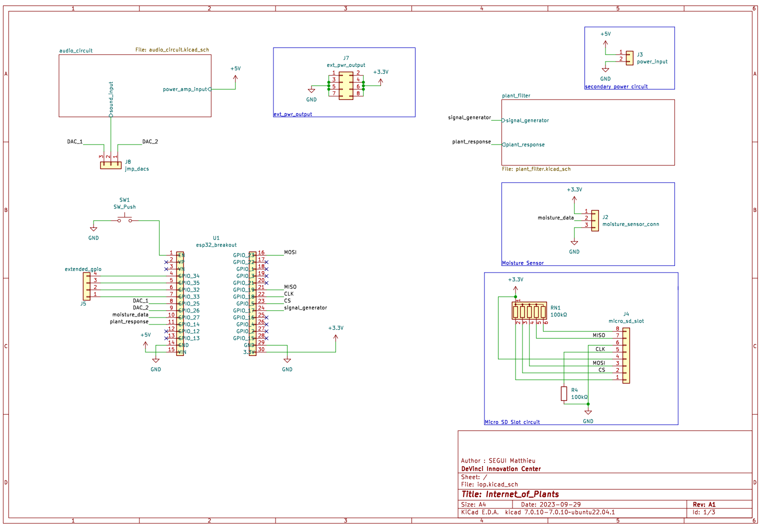

Figure 3: The core of the circuit, the microcontroller, an ESP32 Wroom 32. All the other parts of circuits are plugged in.

The circuit component that allows us to read data from the plant is the electronic filter. This filter has been designed by *Jakub Nikonowicz* and *Łukasz Matuszewski* from *Politechnika Poznańska*. Thanks to them, I adapted it for my application on my embedded device.

This filter is ending by a crocodile clamp that is directly connected to the plant.

The last part of the circuit is the sound output/rendering. This circuit includes a small amplifier, the LM386 from Texas Instruments. The rest of the circuit are components needed in order to induce amplification on the signal without creating to many noise and saturation.

Once the schematic is done, we have to route the tracks. It exists multiple way to route PCB (single-sided, double-sided, multiple layers). We choose

* Microcontroller Unit

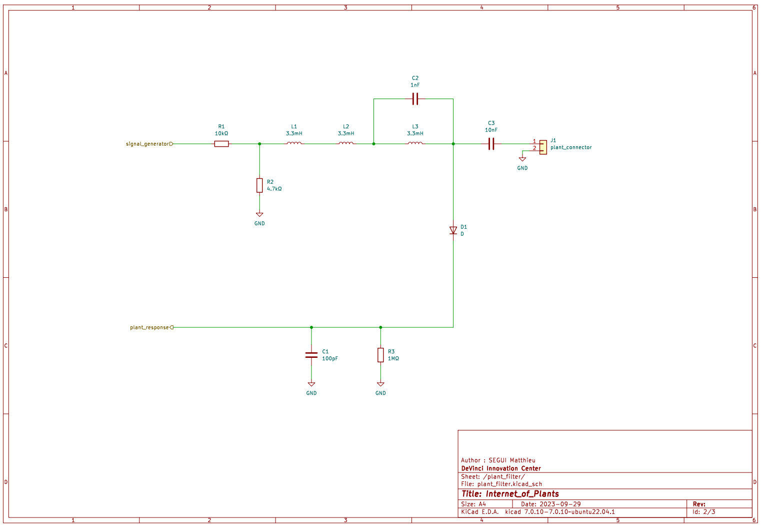

Figure 4: The electronic circuit designed to capture the interaction by analyzing the electronic frequency response. The circuit includes 3 resistors, 3 inductors and 3 capacitors as main components

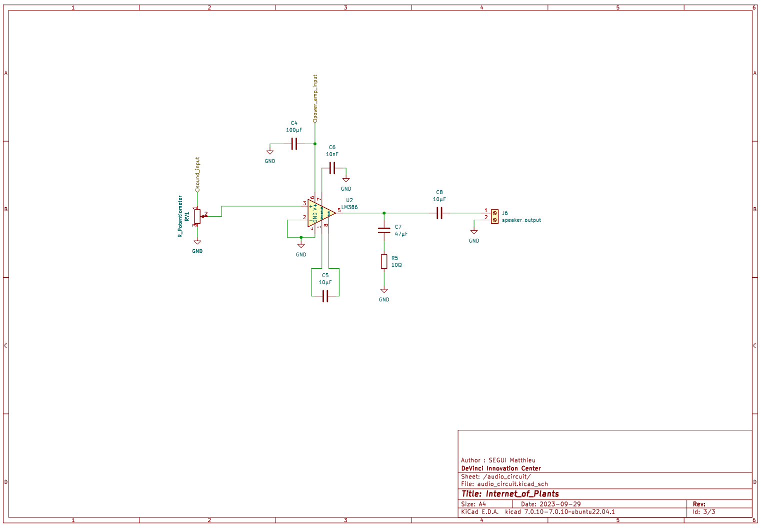

Figure 5: The sound output part of the circuit that is used to render the sound. This part includes a small amplifier, the LM386. The circuit also includes the components necessary to control and handle the amplification (reduce noise and saturation)

double sided, 2 layers on each side of the PCB.

Kicad also allows us to generated a 3D view of the future PCB. This allows us to imagine what the PCB will look like when it will be manufactured.

3.2 Human interaction

The device is able to capture the human interaction with the plant. The touch interaction is inducing changes in the impedance, capacitance and inductance of the plant. Values are captured using the GPIO (General Port Input/Output) 14 of the ESP32 DevKit. This GPIO is able to read analog data and convert them to digital values using analog to digital converter (ADC). The values are a floating point number between add the range here. Values are fluctuating depending on the interaction.

Add a table comparing the values deending on the interaction

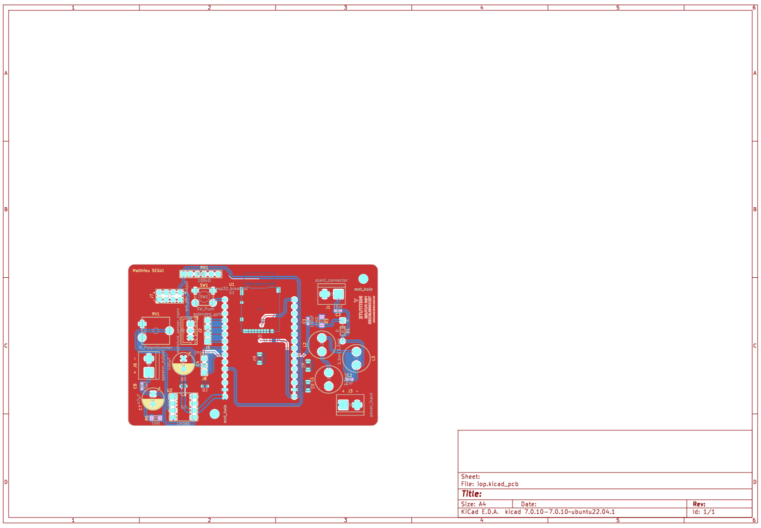

Figure 6: The routed double sided PCB.

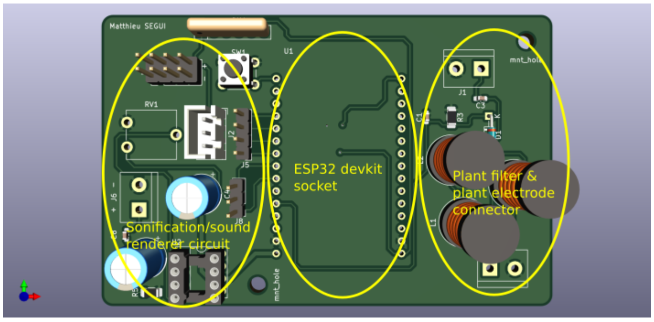

Figure 7: Front 3D rendering of the built PCB. The rendering is done using open source software: Kicad

3.2.1 Sonification on the device

3.2.2 User study

Abstract of user study This study explores human-plant interaction. This study has been conducted in order to understand what kind of interaction we have to detect in order to have the best and more natural kind of interaction with plants. The results will be applied in the Internet of Plants (IoP) project which intends to create a fully connected bio-organ system. The IoP is looking to reduce the gap between humans and plants by creating a symbiotic relationship between nature and technology. We envision a world where our daily objects are responsive.

Introduction Plants represent a full ecosystem of evolution, adaptation and communication.

In the context of the Internet of Plant (IoP) project, this study aims to extract the natural interaction between people and plants. This experiment explores the interactions the IoP device will have to detect to create a symbiotic relation between human and plants. The physical touch is the starting point of a sonification process. Sonification is "the use of non-speech audio to convey information or perceptualize data" [**kramerSonificationReportStatusa**]. Three distinct plant species—*Dypsis lutescens, Pachira glabra, and Dracaena*—are employed as subjects to extract user perceptions and interactions within this framework.

The methodology engages students from the engineering school and two researchers. The participants are asked to interact with the plants and imagine the sounds that could be generated by the plants.

The correlation between plant height and trunk interactions reveals environmental factors impacting human-plant dynamics. Additionally, interactions are categorized based on intensity, spatial displacement, and duration.

Methodology

Participants The study is conducted on 22 participants. Participants are mainly composed of engineering students. The participant set includes 15 males and 7 females. The age of participants is between 19 and 22 years old. Exception for three participants that are older than 22 years old.

The Procedure We introduced the subject telling participants : "We're in the very near future. You are looking at plants that make music when you physically interact with them (it is not actually the case, but imagine it). Explore their capabilities." Using this prompt, we tried not to bridle them to much but approach them to the physical interaction component. Subsequently, participants were given time to explore the potential musical capacities of the plants at their own pace. We conducted the study without providing any guidance during the exploration phase. In instances where participants encountered difficulty initiating exploration, the prompt was reiterated to encourage the participants to explore. This methodological approach was designed to capture the intuitive and natural human-plant interaction. Also, we avoided any kind of communication or talking between 2 participants to reduce the potential bias.

Materials/Tools To proceed and conduct this user study, we chose 3 different plants from 3 different species.

Dracaena: It has long leaves and fragile perceived trunk but also flexible. The plant is 95 cm tall.

Figure 8: The N°1 plant is a *Dracaena*.

Pachira glabra:We chose to use this plant for its large leaves and its wide trunk. The plant is 110 cm tall.

Figure 9: The N°2 plant is a *Pachira glabra*.

Dypsis lutescens: The *Dypsis lutescens* is composed of many trunks and stems. On top of that, the leaves are numerous and tight. The plant is ... tall.

Figure 10: The N°3 plant is a *Dypsis lutescens*.

The experimental space The experimental space featured three distinct levels of height, each corresponding to one of the three plants introduced to participants.

Figure 11: User study space setup. The setup is built from our lab space.

Data collection To capture the participant's interactions with the plants, a collaborative approach was adopted, involving two researchers to provide dual perspectives. Throughout the exploration phase, both researchers took notes, documenting the diverse ways in which participants engaged with the three distinct plants. The researchers explicitly specified the plant involved in the interaction in order to extract special features related to a specific plant.

The written notes retrieved descriptions of participants' actions, movements and interactions. The dual-observer strategy tends to reduce the potential biased.

At the beginning of the experiment, the *Dypsis lutescens* was on the floor, the *Dracaena* was on a chair and the *Pachira Glabra* was on a table. At the middle of the experiment, we switched the *Dypsis lutescens* and the *Pachira Glabra* to see if the participants would interact differently with the plants. The set-up of the experiment is shown in Figure 11.

Results The data given by the user study allowed us to define 5 main types of interaction. Those interactions are defined by the way the user interacts with the plant. The 5 main types of interaction are :

- Grasp : user uses the whole hand to grab trunk or leaves.
- Pinch : user uses 2 to 3 digits to grab trunk or leaves.
- Slide : user uses his/her hand or finger to slide on the plant whether is on a leave or on the trunk. The action is continuous.
- Pet : user uses his/her hand to cuddle the plant or to pass through the leaves. The user is moving his/her hand in space. She/he is not staying still or staying on a particular object.
- Tam Tam : user taps on the plant mainly using the whole hand.

Looking at the results, we extracted the table 1.

Plant/Interaction	Group 1		Group 2	Group 3	
	Grasp	Pinch	Slide	Pet	Tam Tam
Plant N°1	4	8	4	4	2
Plant N°2	9	3	3	3	10
Plant N°3	10	1	5	7	3
Total	23	12	12	14	15

Table 1: Raw results extracted from the user study

With the extraction of the result we were able to design a bar chart. The graph is grouping the interactions by plant. The height of the bar is the number of participants that performed the interaction. The graph is shown in figure 11.

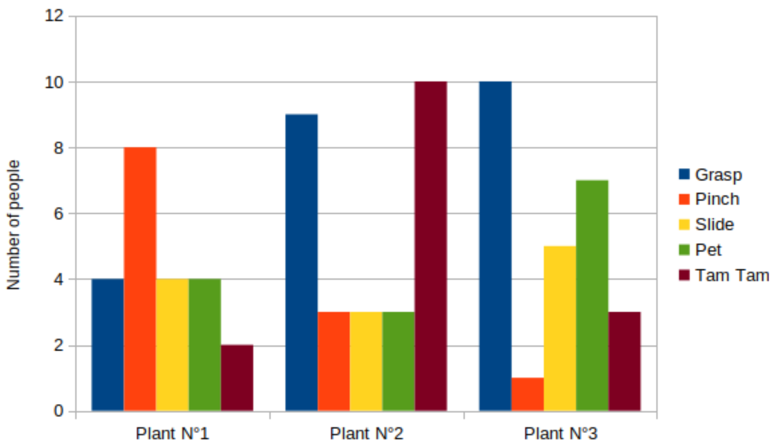

Figure 12: Bar chart that is extracting the main types of interaction regarding each plants.

In the end, of the 22 participants, 15 were already familiar with the project and 7 were not.

Discussion Looking at the results, the interaction were various depending on the plant. Thus, we can extract main interactions that are linked to the plant type. Looking at table 1, people are more inclined to use their hands as tam tam or grasp the *Pachira glabra*. However, for the *Dracaena* users prefer to pinch the trunk or leave. Participants decided to grasp whether a pack of trunk or leaves when it came to *Dypsis lutescens*. This is induced by many factors including the leaves shape, the width of the trunk.

It was observed that when the plants were positioned at higher elevations on the table, individuals tended to engage more with the trunk of the plants.

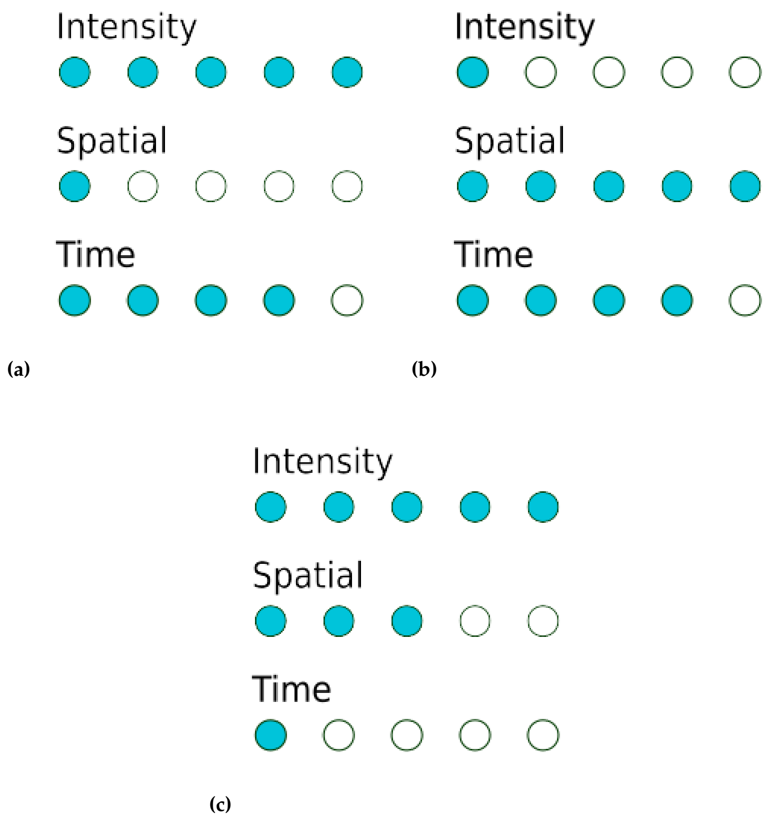

Figure 13: Figure showing graphically the intensity of the 3 types of factors we defined. (a) Group 1 : pinch and grasp. (b) Group 2 : slide. (c) Group 3 : pet and tam tam.

Looking at table 1, we decided to group interaction. This was done by grouping type of interaction depending on 3 main factors :

- The intensity factor : what is the intensity of the interaction (ex : pinch is lighter than grasp)
- The spatial factor : what is the interaction displacement.
- The duration factor : what is the interaction duration (ex : tam tam is instantaneous).

The "Group 1" includes the pinch and grasp interaction. Indeed, looking at the 3 factors we defined, the pinch and grasp are high in intensity and long in duration but people stay still in space. This group of interaction can be defined as **binary interaction**. The user is either grasping or not.

The "Group 2" includes the slide. The slide interaction is long in time, it moves in space but low in intensity. This group of interaction can be defined as **continuous interaction**.

Whereas, the "Group 3" includes the pet and Tam Tam. These 2 interactions are really high in intensity, people usually tam tam and pet in different places but those interactions are short in time. This group is defined as **repetitive interaction**. The user is repeating the same action over and over again.

The participants we interviewed introduced a bias in the results. They were all students from the engineering school and thus, they all had a similar background. Some of them were already familiar with the project.

Conclusion During our study on the Internet of Plant project, we've captured insights into how people might interact with plants in a future where they make music through touch.

Our three chosen plants influenced how participants engaged with them. We observed everything from gentle petting to energetic drumming on the plants. Interestingly, we found that when the plants were higher up, participants tended to focus more on the trunk.

By grouping interactions based on factors like intensity and duration, we gained a clearer picture of how people approached these musical plants. It turns out that certain interactions, like grasping and pinching, were more common, while others, like sliding, had their own distinct appeal.

Regarding to the results we thought about what could be done with the defined interactions. For instance, the sound generated from the interaction could be linked to the kind of interaction. People doing Tam Tam on the plant will expect a drum sound. Whereas, people performing a slide will expect a sound closer to a continuous organ sound. The possibilities are endless and the only restrictions are the capabilities of the device capturing the interaction.

3.3 Final product and future work

The final product is an embedded device that include signal filtering, wireless communication and embedded sonification.

To improve the device, the PCB could be reduced in size using a surface mounted device (SMD) ESP32 instead of a DevKit. I already started to work on a new version of the device. This version is only designed on Kicad and not prototyped. The rest of circuit is similar.

Add schematic of the new PCB

A better audio amplifier could be explored in order to reduce the distortion of the sound. Adding an external digital to analog converter is also a possibility in order to upgrade the output. However, this possibility adds new components that will increase the size. Exploring the I2S protocol opens better output. The I2S protocol is a protocol talk quickly about the I2S protocol

3.4 Conclusion

4 Internet of Plants

4.1 Overview

The Internet of Plants, also called IoP, is a concept that aims to interconnect the plant device previously built. This in order to empower the device capabilities and to provide a better user experience. This project includes:

- A better sound quality by using professional sonification software
- The ability to create a full artistic experience by creating a distributed instrument
- Refining the interaction with the plant by using more complex data analyses

4.2 Communication

The communication system is based on WiFi technology. The ESP32 has specific wireless capabilities. The server and the ESP32 devices are connected to the same network. The ESP32 sends the raw data to the server using IP**. This is done through a TCP †† socket open between the server and one ESP32. The server can open as many socket as there are clients. The data sent using a string. A "" start character and a ";
n" stop character are used to prevent the messages to be truncated and still processed on the server side. The IP protocol (whether it is on WiFi or Ethernet) has been chosen for this application for several reasons:

- Allow high bandwidth
- Available in most places
- Allow connection of multiple devices
- Already available on the server and on the ESP32

Other communication protocols have been benchmarked. Here is a table that summarizes the choice:

The result of this table confirms that WiFi is the right choice for our specific application.

4.3 Server

The server is a small fanless computer running Lubuntu. Lubuntu is a lighter version of Ubuntu that includes LXQt as desktop environnement. The choice of a distribution with graphical interface is induced by the use of *Pure Data* as sonification software.

Pure Data (PD) is an open-source visual programming language designed primarily for creating interactive multimedia applications, particularly in

Protocol	IP	Bluetooth	BLE	Zigbee
Handle multiple connections	Yes	No	No	Yes
Requires additional hardware	No	No	No	Yes
Subject to interference	Yes	Few	Few	Yes
Energy efficiency (using a battery)	Days	Months	Years	Years

Table 2: Comparison between different communication protocol to find the one that will suits our needs the best.

** Internet Protocol
†† Transmission Control Protocol

the fields of audio, video, and graphical processing. Pure Data is part of a family of patcher programming languages, which also includes Max/MSP. Unlike traditional text-based programming, PD uses a graphical interface where users connect "objects" with virtual patch cables to create complex data flows and signal processing chains. Its modular design allows for real-time manipulation of sound and graphics, making it a powerful tool for artists, musicians, and researchers interested in exploring experimental media.

Pure Data requires, in a development environnement, a graphical interface to test and debug. The Pure Data patch receive the data through a TCP socket. The data is processed through several operations. Then, if a threshold is passed, an interaction happened and the music is triggered. The music is outputted through the item *DAC* which means Digital to Analog Converter. The digital input from pure data is converted to a sound that speakers can output.

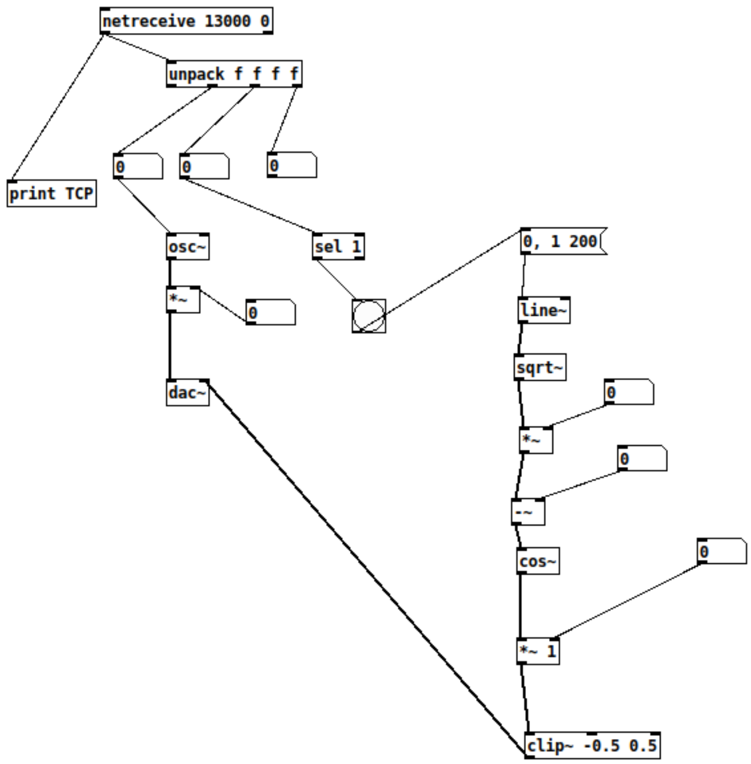

Figure 14: Basic *Pure Data* patch that is used for sonification of the data of the plant. In case of an art exhibition, the Pure Data patch can be upgraded to meet the artist needs

Pure Data is a sonification software that require data as input. In order to get and process the data, we designed a Python based software. The software is object oriented. The standalone IoP modules connect using WiFi to the receiver module of the software. The connection is made using TCP socket from the ESP32 to the server. The main module of the software then creates software abstraction of the standalone module. The abstraction module is processing and storing all the processed data. The main module then send the processed data to Pure Data patch using also local TCP socket.

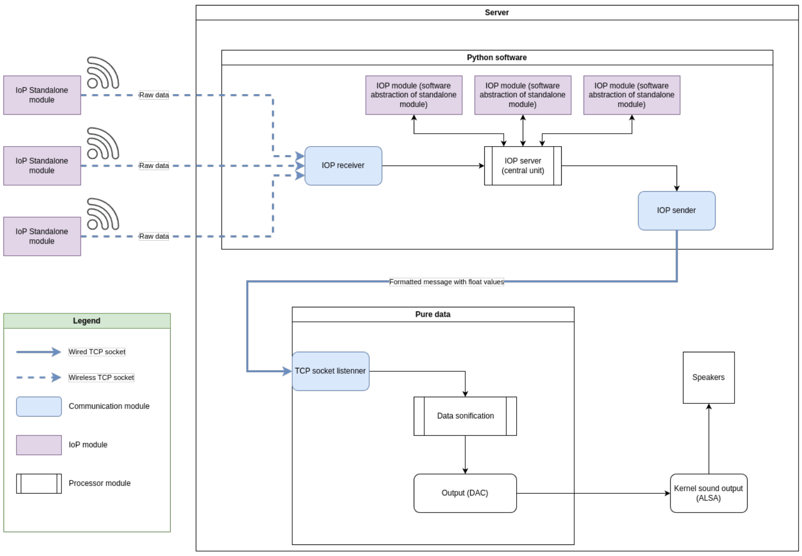

Figure 15: Architecture diagram of Internet of Plants project centered on server-side.

4.4 Deployment

The server software is easily deployable. The software includes a shell script to deploy the server service. Indeed, the server relies on a *systemd* linux service. *Systemd* [23] is a Linux software that manage application that runs *daemons* or services. *Daemons* are pieces of software that run in background of the operating system. They are mainly started at the during the boot of the operating system.

The server is deployed that way so the software starts with the operating system. It waits for the network interfaces to be up and running and opens the socket. The installation tool install Python dependencies, fill in the templated service file, install the service and enable it. The server is able to receive data from IoP standalone modules and use Pure Data software for sonification. The last step is to connect a jack speaker to the jack builtin output.

On the IoP standalone module side, it requires a software that is able to upload firmware to an ESP32 MCU. I recommend using PlatformIO which is an open source embedded software development platform. The firmware is developed using this platform. The source code is written in C++ using the Arduino framework. You flash the firmware to the chip after setting up the WiFi credentials. The module sends all the retrieved data to the server.

4.4.1 Distributed instruments

This IoP architecture enables possibilities on deploying a distributed instrument. It is possible to deploy several IoP standalone modules, in different plants and build a entire musical instrument. Modules reach out to the server and the server link an ID to the different connected devices. The data is sent to Pure Data and using the software, you can create many sounds depending on the module (and thus plant) origin. Pure Data offers a fine control over pitch, sound, rhythm, tone and much more.

4.5 output

4.5.1 Art exhibition

To push further the distributed instrument, it is possible to build an entire musical experience for an art exhibition. The immersive experience can take place as a fully connected forest. The music would vary depending on the touch interaction that people have with the plants.

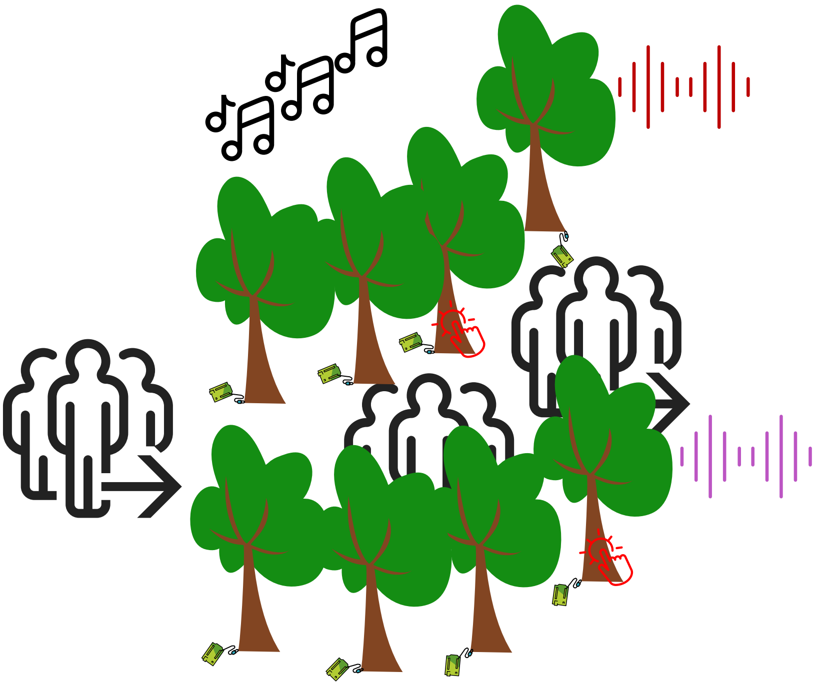

Figure 16: Schematic of the IoP art exhibition. The music varies depending on the interaction that people have with the installation. People are immersed into the full musical and sonification experience.

This exhibition could allow people to rethink the way the see and interact with plants. Plants are not seen anymore as decoration object but as a living being. The living being is here highlighted by the fact that plants can now express their state. The humidity level, the light intensity and other state signs are modifying the plant reaction.

Musicians can also work in pair with plants to create songs using music from the plants. The music coming from the plant is fully configurable with the sonification software.

4.5.2 Final product, limitations and future work

Final product is a software that allows the connection between multiple standalone IoP modules and a sonification software, Pure Data. The software handle multiple connection and apply a filtering and cleaning on the data retrieved. The data is then sent to Pure Data for sonification.

On the limitation side, the use of WiFi ease a lot the deployment of the system, however

4.6 Conclusion

Figure 17: Server-module demo. In this specific use case, the module is connected by wire to a computer. Otherwise, the module is usable wirelessly. The computer is acting as a server. On this version of the demo, the screen is displaying a figure that is evolving depending on the touch interaction. The computer, acting as the server, is producing the sound using Pure Data software.

5 Conclusion

References

Here are the references in citation order.

[1] John M Carroll. 'HUMAN-COMPUTER INTERACTION: Psychology as a Science of Design'. In: () (cited on page 1).

[2] Charles Hall and Melinda Knuth. 'An Update of the Literature Supporting the Well-Being BeneÂ¢ts of Plants: A Review of the Emotional and Mental Health BeneÂ¢ts of Plants'. In: (2019) (cited on page 3).

[3] Greg Watts. 'The Effects of "Greening" Urban Areas on the Perceptions of Tranquillity'. In: *Urban Forestry & Urban Greening* 26 (Aug. 2017), pp. 11–17. DOI: 10.1016/j.ufug.2017.05.010. (Visited on 06/26/2024) (cited on page 3).

[4] Harumi Ikei et al. 'The Physiological and Psychological Relaxing Effects of Viewing Rose Flowers in Office Workers'. In: *Journal of Physiological Anthropology* 33.1 (Dec. 2014), p. 6. DOI: 10.1186/1880-6805-33-6. (Visited on 06/26/2024) (cited on page 3).

[5] Olivia Seow et al. 'Pudica: A Framework For Designing Augmented Human-Flora Interaction'. In: *Augmented Humans 2022*. Kashiwa, Chiba Japan: ACM, Mar. 2022, pp. 40–45. DOI: 10.1145/3519391.3519394. (Visited on 10/24/2022) (cited on page 3).

[6] Alexander G. Volkov et al. '*Mimosa Pudica* : Electrical and Mechanical Stimulation of Plant Movements'. In: *Plant, Cell & Environment* 33.2 (Feb. 2010), pp. 163–173. DOI: 10.1111/j.1365-3040.2009.02066.x. (Visited on 05/26/2024) (cited on page 3).

[7] Munehiko Sato, Ivan Poupyrev, and Chris Harrison. 'Touché: Enhancing Touch Interaction on Humans, Screens, Liquids, and Everyday Objects'. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. Austin Texas USA: ACM, May 2012, pp. 483–492. DOI: 10.1145/2207676.2207743. (Visited on 05/26/2024) (cited on pages 3, 4).

[8] Ivan Poupyrev et al. 'Botanicus Interacticus: Interactive Plants Technology'. In: *ACM SIGGRAPH 2012 Emerging Technologies*. Los Angeles California: ACM, Aug. 2012, pp. 1–1. DOI: 10.1145/2343456.2343460. (Visited on 05/26/2024) (cited on page 4).

[9] Colin Honigman, Jordan Hochenbaum, and Ajay Kapur. 'Techniques in Swept Frequency Capacitive Sensing: An Open Source Approach'. In: () (cited on page 4).

[10] Ken Hinckley and Mike Sinclair. 'Touch-Sensing Input Devices'. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems the CHI Is the Limit - CHI '99*. Pittsburgh, Pennsylvania, United States: ACM Press, 1999, pp. 223–230. DOI: 10.1145/302979.303045. (Visited on 08/18/2024) (cited on page 4).

[11] Simon Olberding et al. 'A Cuttable Multi-Touch Sensor'. In: *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology*. St. Andrews Scotland, United Kingdom: ACM, Oct. 2013, pp. 245–254. DOI: 10.1145/2501988.2502048. (Visited on 08/18/2024) (cited on page 4).

[12] T Hermann and H Ritter. 'Listen to Your Data: Model-Based Sonification for Data Analysis'. In: () (cited on pages 4, 5).

[13] Mark Ballora et al. 'Use of sonification in the detection of anomalous events'. In: *Multisensor, Multisource Information Fusion: Architectures, Algorithms, and Applications 2012*. Vol. 8407. SPIE. 2012, pp. 213–219 (cited on page 5).

[14] Adian F Rochim, Mukhlish A Aziz, and Adnan Fauzi. 'Design Log Management System of Computer Network Devices Infrastructures Based on ELK Stack'. In: *2019 International Conference on Electrical Engineering and Computer Science (ICECOS)*. IEEE. 2019, pp. 338–342 (cited on page 5).

[15] Gareth Loy. 'Musicians Make a Standard: The MIDI Phenomenon'. In: *Computer Music Journal* 9.4 (1985), p. 8. DOI: 10.2307/3679619 (cited on page 5).

[16] I Fazenda, Sao Paulo, and I S Junior. 'Proceedings of the International Conference on New Interfaces for Musical Expression'. In: () (cited on page 5).

[17] I Fazenda, Sao Paulo, and I S Junior. 'Proceedings of the International Conference on New Interfaces for Musical Expression'. In: () (cited on page 5).

[18] Tanvir Hussain and Md Mejbaul Haque. 'AVR Microcontroller Implementation for Customized Sound Generation'. In: *International Journal of Electrical and Computer Engineering (IJECE)* 2.1 (Nov. 2011), pp. 112–119. DOI: 10.11591/ijece.v2i1.139 (cited on page 6).

[19] Bassam Shaer et al. 'Interactive Capacitive Touch Music Table with Embedded Microcontrollers'. In: *The Journal of Supercomputing* 76.11 (Nov. 2020), pp. 8845–8865. DOI: 10.1007/s11227-020-03167-4 (cited on page 6).

[20] Khurshid Aliev et al. 'Internet of Plants Application for Smart Agriculture'. In: *International Journal of Advanced Computer Science and Applications* 9.4 (2018). DOI: 10.14569/IJACSA.2018.090458. (Visited on 08/24/2024) (cited on page 6).

[21] Peter G. Steeneken et al. 'Sensors in Agriculture: Towards an Internet of Plants'. In: *Nature Reviews Methods Primers* 3.1 (Aug. 2023), p. 60. DOI: 10.1038/s43586-023-00250-x. (Visited on 08/24/2024) (cited on page 7).

[22] Masaharu Kitano et al. 'Internet of Plants (IoP) Empowers Bottom-up Innovations in Greenhouse Horticulture'. In: *Environment Control in Biology* 60.1 (Jan. 2022), pp. 3–12. DOI: 10.2525/ecb.60.3. (Visited on 08/24/2024) (cited on page 7).

[23] David Both. 'systemd'. In: *Using and Administering Linux: Volume 2: Zero to SysAdmin: Advanced Topics*. Berkeley, CA: Apress, 2020, pp. 379–410. DOI: 10.1007/978-1-4842-5455-4_13 (cited on page 19).