INSTITUTE FOR FUTURE TECHNOLOGIES
DE VINCI HIGHER EDUCATION

Master thesis

How can sensing techniques redefine our interaction with plants ?

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Contents

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 eager to take on 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

1.3 Problematic

1.4 Research domain

Research domains on the human-plant interaction are wide. The HCI* field is focused during this master thesis. HCI gather all the technologies that allows human to interact with computer. However, it usually only is a new way of interaction, there the plant is a living component that brings its own sensibility and needs (watering, lighting...).

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

1.5 Contributions

* Human Computer Interface

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 [1] 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 [2]. An experience has been conducted in offices by Ikei and al [3] 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. [4] 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 [5]. 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.

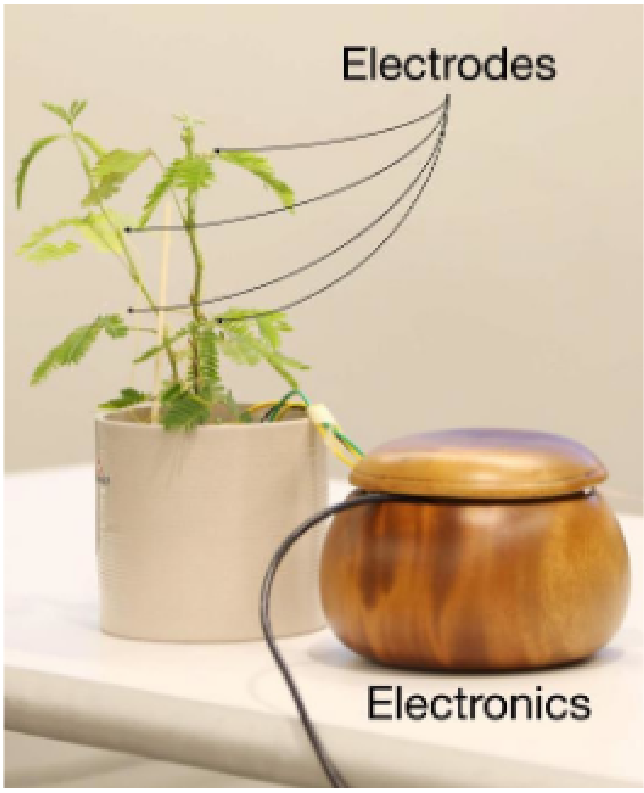


Figure 1: *Pudica framework* made by Seow and al. The *Mimosa Pudica* is a special plant that react to the interaction by closing its leaves. The framework captures the electrical impulse and then interprets that an interaction happened.

Sato and al. used the process of capacitive sensing to detect interaction with objects of our daily lives [6]. 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. [7] 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. [8] 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. [9] 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 [10]. 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 [6]. 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 on microcontrollers

MCUs‡ [11] is a kind of small computer. Those devices can be used to generate sound. The most common way of doing electronical music is to

† Open source compute unit
‡ microcontrollers

use MIDI[§] [12]. 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 [13][14]. 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 with many microcontrollers such as a small 8 bits AVR microcontrollers (ATmega32) [15]. 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. [16] 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.

2.1.6 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

§ Musical Instrument Digital Interface
¶ Digital to Analog Converter

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. [17] 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 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. [18], 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. [19] 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

Internet of Things

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*.

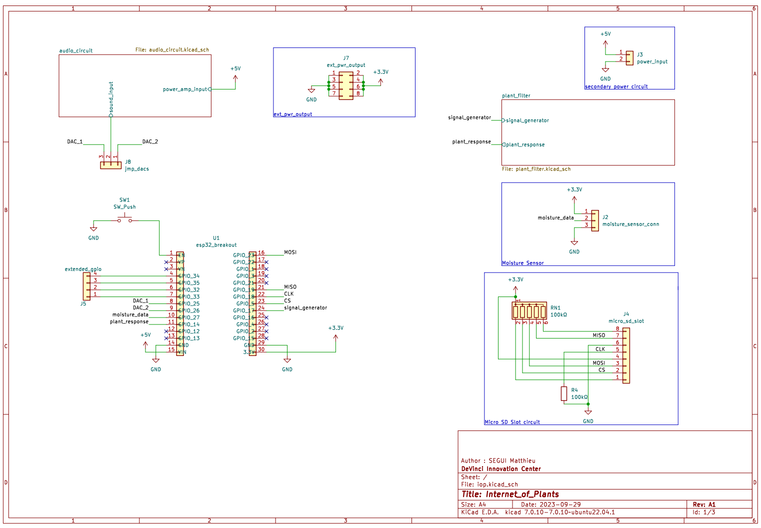


Figure 3: The core of the circuit, the microcontroller, an ESP32 Wroom 32. All the other parts of circuits are plugged in.

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.

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

* Microcontroller Unit

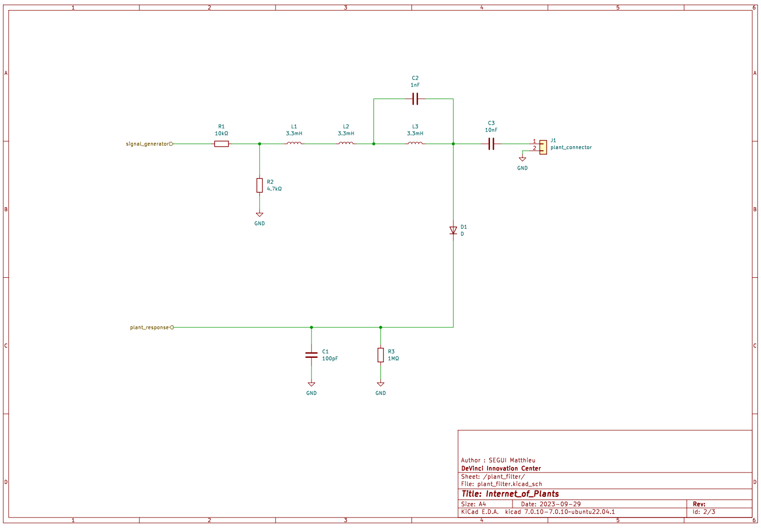


Figure 4: The electronic circuit designed to capture the interaction by analyzing the electronic frequency response. The circuit includes 3 resistors, 3 inductors and 3 capacitors as main components

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

3.2.1 ezaea

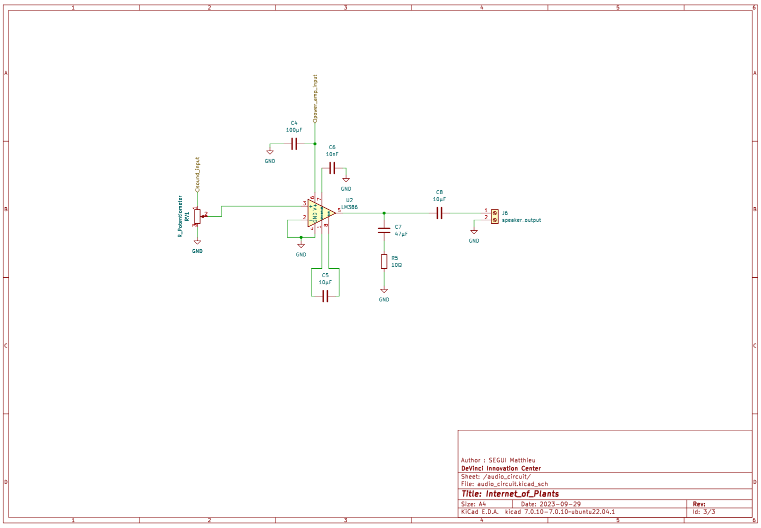


Figure 5: The sound output part of the circuit that is used to render the sound. This part includes a small amplifier, the LM386. The circuit also includes the components necessary to control and handle the amplification (reduce noise and saturation)

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" [20]. 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

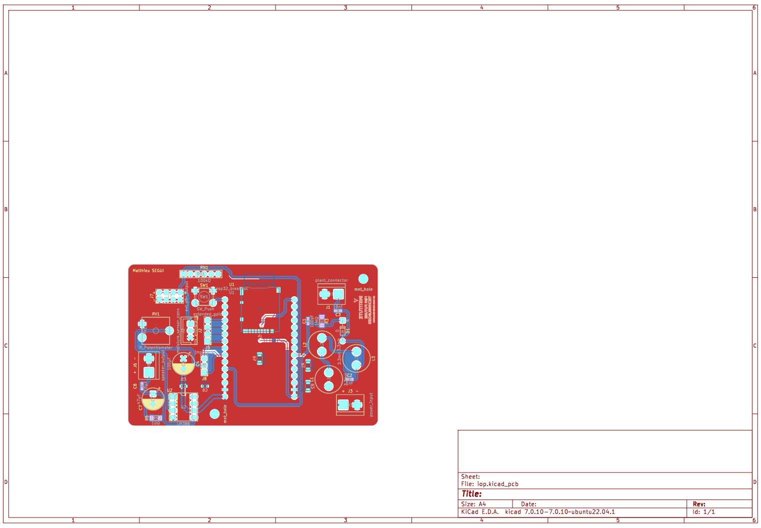


Figure 6: The routed double sided PCB.

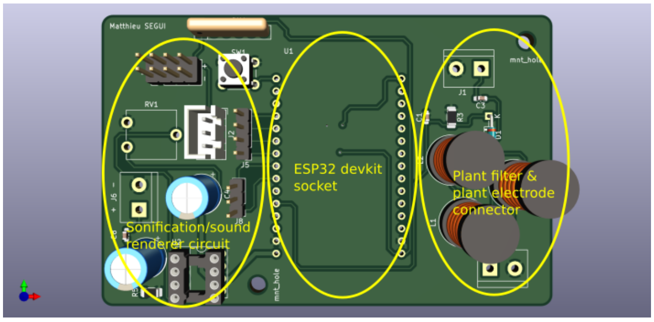


Figure 7: Front 3D rendering of the built PCB. The rendering is done using open source software: Kicad

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.

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

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

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.

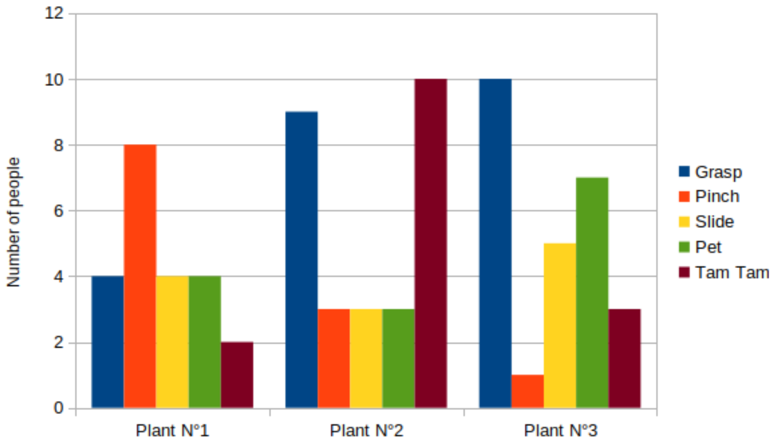


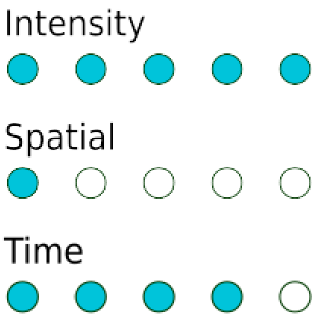
Figure 12: Bar chart that is extracting the main types of interaction regarding each plants.

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

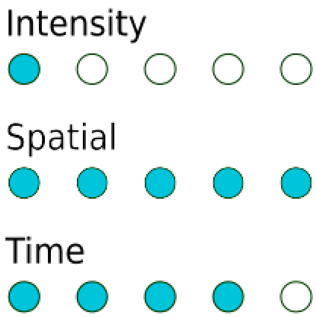
Discussion Looking at the results, the interaction were various depending on the plant. Thus, we can extract main interactions that are linked to the plant type. Looking at table 1, people are more inclined to use their hands as tam tam or grasp the *Pachira glabra*. However, for the *Dracaena* users 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.

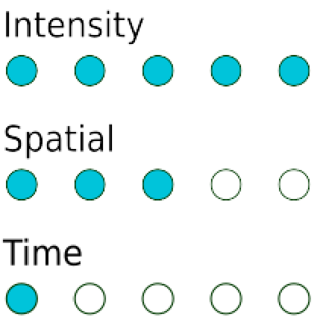
Looking at table 1, we decided to group interaction. This was done by grouping type of interaction depending on 3 main factors :



(a)



(b)



(c)

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.

- 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 ...

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 protocol have been benchmarked. Here is a table that summarizes the choice:

Protocol	IP (WiFi/Ethernet)	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

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.

** Internet Protocol
†† Transmission Control Protocol

4.4 Deployment and application

4.4.1 Distributed instruments

4.4.2 Art exhibition

4.5 Conclusion

5 Conclusion

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