Interactive plants as sound art project

Toningenieurs-Projekt

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Abstract

This project report describes the idea and implementation of an interactive plant which reacts to being touched on the leaves with different kinds of sound. Sound design as a means of communicating the health or irrigation of the vegetation will be discussed. A flower which was properly watered, conveys positive emotions when petted, whereas it will sound noticeably negative when it is not. Different use cases and end-users will be discussed as well. The technical realization will be portrayed in detail. The goal is to create a mobile, energy- and cost-efficient device that can be used with a variety of plants. The choice of sensors for measuring touch and moisture of the soil but also different ways for a power supply or audio playback will be debated. All of the electronics will be hidden inside an enclosure to create the impression of a regular flower in a regular pot. Eventually, the 'talking plant', also called 'moody plant', took part in an accelerator program for start-ups. The learnings and results of this journey will be presented.

Kurzfassung

Diese Arbeit befasst sich mit der Idee und Umsetzung einer interaktiven Pflanze, die auf Berührung mit unterschiedlichen Klängen reagiert. Sound Design als Mittel zur Kommunikation des (Bewässerungs-)Zustandes der Pflanze wird besprochen: Eine gut bewässerte Pflanze vermittelt eine positive Stimmung während eine zu trockene Pflanze klar negativ klingende Sounds von sich gibt. Unterschiedliche mögliche Anwendungsbereiche und Nutzer werden diskutiert. Die Technische Umsetzung wird im Detail erläutert. Das Ziel ist es, einen mobilen, energie- und kosteneffizienten Apaprat zu bauen, der mit unterschiedlichen Pflanzen funktioniert. Die Wahl der Sensoren zur Berührungserkennung und Feuchtigkeitsmessung, aber auch die Möglichkeiten zur Umsetzung der Spannungsversorgung und der Audio-Wiedergabe werden besprochen. Es sollen alle Bauteile versteckt sein, sodass nach außen der Eindruck einer normalen Pflanze in einem normalen Topf entsteht. Schlussendlich nahm die 'sprechende Pflanze', auch moody plant genannt, an einem Accelerator Program für Start-Ups teil. Die Erkenntnisse und Ergebnisse dieser Reise werden reflektiert.

Contents

1 Introduction and Concept

Over 90% of households in the United States of America own or plan to buy house plants[2], a majority of companies buy and tend to them as well. Especially since the COVID-19 pandemic the number of self-declared plant parents has grown steadily.

Apart from being a beautiful addition to your home reasons such as psychological benefits, air purification and stress reduction are often cited when asked why people like to own plants. In a quickly moving world they can be seen as a slow and calm counterpart to the constant stimuli in our daily lives. Often they are regarded as 'company' and owners can even create an emotional connection to them, much like with a pet.

Unfortunately house plants are not always easy to take care of and in many cases they end up dying prematurely. This may be due to a lack of knowledge about the plant's needs, a lack of time or interest to do the research on your own. Often they also just get neglected because there are a thousand other things on everybody's mind and since plant cannot communicate their needs, they often go unattended and untreated

This is exactly why the 'moody plant' project was created. It is a flower pot with multiple sensors and acoustic feedback which lets the owner know how their herbal pet is doing and what it needs to stay healthy.

The concept consists of two parts:

- Find out if all its basic needs are fulfilled:
  To do that, there need to be sensors that measure moisture, lighting and temperature. Depending on which plant you choose, thresholds are chosen individually for each sensor in which the vegetation tends to do well. The sensors are connected to a micro-controller with Bluetooth/WiFi capabilities so the type of flower can be changed remotely by the user. This type of sensor-equipped flower pot already exists in various forms. The novelty of the project comes from the seconds part:

- Feedback and encouraged interaction:
  The feedback on how well the plant is doing, is given acoustically with animal like sounds. If the sensors determine that everything is the way it should be, the sounds tend to be happy or content. On the other hand, the sounds can be sad or aggressive if for example there is too little or too much water. With some more elaborate sound design a distinction between different needs of the flower can be made. With this prosody based approach and its similarity to actual pets, a social and emotional connection can be established. The idea is to keep the owner more engaged and avoid neglect, just like you would not ignore your cat or dog if they let you know they are hungry.
  The trigger for the sonic feedback, similar to living pets, is by touching or rather petting the plant. There is a custom capacitive touch sensor integrated in the electronics of the pot, that registers whenever you touch a blossom or stroke a leave. This way, there is no need to ever check an app, go online or look up sensor values. The experience is purely off-line, minimal effort and encouraged by copying the behaviour of an actual pet. Just like the 'Tamagotchi' was very popular with a

similar approach, this organic version of said toy should also increase the owners interaction with the plant.

2 Comparable Products

As expected, there are already plant pots available on the market that feature integrated sensors to help maintain plant health. These products, commonly referred to as smart planters, utilize real-time sensor measurements to monitor factors such as moisture, light, and temperature. Some of these products even claim to measure soil nutrient levels and offer automated watering and nutrient distribution. Additionally, certain smart planters incorporate artificial lighting to ensure optimal plant growth. However, the main distinction of this project lies in its interactivity. Most conventional products provide feedback through numbers, graphs, or color changes on smartphone screens or hardware devices.

2.1 PLANTSIO Ivy

Ivy also features sensors to assess the plant's health condition and includes a separate tank for automated watering. However, this smart planter aims to enhance the plant care experience by introducing a unique form of interaction. Instead of relying on a smartphone screen, Ivy incorporates an external screen that displays the plant's face, which changes expressions to indicate its health status. This visual representation adds a sense of liveliness and enhances user engagement. On the downside, this product is relatively expensive and only available in one size, which may be too small for larger plants. According to their Indiegogo page, the regular price for one pot is approximately 100 euros.

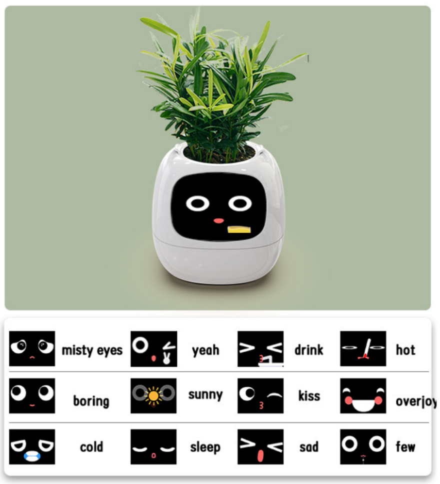


Figure 1: PLANTSIO Ivy

2.2 BOTANICUS INTERACTICUS

Figure 2: BOTANICUS INTERACTICUS

The Botanicus Interacticus project[7] primarily focuses on tactile interactions and gesture control. It is an example of the practical application of the "swept frequency touch sensing" approach, as described in the publication by Poupyrev et al.[9]. It was exhibited at the SIGGRAPH emerging technologies exhibition in Los Angeles in collaboration with Studio NAND, as more of an artistic project than a consumer product designed to assist with plant care. The project involved triggering ambient noises and colorful visuals on a screen behind the plant based on touch interactions. Unlike the previously mentioned products, its main goal was not to keep the plant alive, and it was not intended for commercial sale.

In my design, I aim to combine elements from these different products to create the most engaging user experience.

3 Sound and Interaction Design

A main goal of the interaction design was to keep it natural and intuitive. Despite the presence of a micro-controller and additional electronics concealed inside the pot, there should be no direct interaction with mechanical, electrical, or digital components. None of the hardware should be visible and there should be no need to use an app or a computer program to get started.

Instead of clicking buttons on a mouse, keyboard, or the touch-screen of a smartphone, you stroke the leaves of the plant. Instead of reading data graphs on a display, you listen to the affection in the voice, that the plant seemingly produces.

Through affectionate noises, the user learns how the plant is feeling. By watering, changing the temperature, or adjusting sunlight, they can attempt to change the mood of the vegetation. When the mood changes in a positive manner, the user is rewarded with happier sound snippets, and they learn what the plant likes and how to keep it happy and healthy.

A major benefit of this natural type of interaction is the development of real affection towards the 'moody plant' [1]. This phenomenon of developing an emotional relationship with inanimate or non-living objects can be seen with the 'Tamagotchi' or Sony's robot dog 'AIBO' [10]. Even an ethical responsibility can be developed this way[6]. This is supposed to result in more time spent interacting with house plants resulting in better care and longer plant lives.

3.1 Types of moods

The most significant distinction a user must be able to make is whether their flower is healthy or not. Additionally there should be a spectrum covering all shades of content or discontent, not just a binary distinction. If they haven't watered the soil for a month the acoustic reaction can't be the same as if they had forgotten for only a few days.

There are multiple sensors intended to estimate whether the circumstances allow the herbage to flourish. This includes measurements for soil moisture, temperature or exposure to sunlight. Consequently, the sound bits must allow the user to differentiate between various reasons for the plant's dissatisfaction. If the temperature gets too low, it might start producing sounds of shivering. If it gets too hot, it may pant. A lack of light might make it more tired and yawn, whereas too much light might make it very irritable. These kinds of subtle distinctions have yet to be implemented.

3.2 Types of sound creation

There are two major approaches to sound creation, each with its own benefits and disadvantages:

- Parameter-based synthesis:
  With this approach, the sensor data would be collected and transformed into various acoustic parameters such as pitch, distortion, filtering, ADSR curves or something similar. The advantage of this approach is an infinite amount of possible variations and an exact representation of all variations of sensor data. There also is no need for an excessive amount of memory since there are no or very little samples that need to be saved.
  Unfortunately, it is very difficult to create intuitive sounds that are recognized as happy, thirsty or cold. Additionally the sounds may sound rather unnatural which do not quite as easily give the impression of an animate object which makes it harder to emotionally connect with the plant.

- Sample-based approach:
  Recording sounds, made for example by the human voice, can be very precise in portraying a certain emotion, especially with some post-processing. Well-known sounds of our favorite animals can be imitated, leading to very intuitively recognizable sounds. Consequently, this approach requires significantly more memory for storing samples. If there are not enough different recordings, the repetition of the same noises may start to annoy the user and again the impression of a living being gets diminished. With methods like pitch-shifting, time stretching, filtering, etc., the sound variations can be extended without the need for an excessive number of samples.
  In the end the second approach was chosen because of the recognizability of emotions within the sound samples.

4 Technical implementation

In this section the different components of the project will be discussed. How they work, why they have been chosen this way and what the alternatives were. Previous iterations with different hardware implementations and ideas for future versions will be mentioned as well. The discussed hardware includes the micro-controller, environmental sensors, a touch sensor, battery management, audio playback and the flower pot.

4.1 Choice of micro-controller

Arduino Pro Mini + MozziByte Audio Shield

When the project started, the micro controller of choice was the Arduino Pro Mini connected to a MozziByte audio shield. With an Arduino it is quite easy to get started and with the audio shield one can play audio from the get go. This combination cost about 30€, which can be acceptable for prototyping but it is not very cost-effective. Parameters like clock speed, memory or interfaces are not very impressive either. At this point in time, the micro controller was still connected to a PC via USB and most of the project's signal processing was done there.

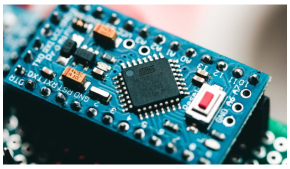
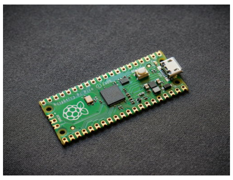
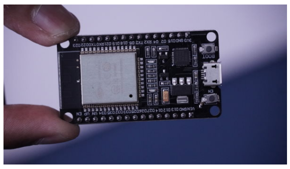
Raspberry Pi Pico

The next goal was to get a little more cost-efficient and become independent from any PC to do the signal processing. With the Raspberry Pi Pico a significantly faster processor was chosen and the entirety of the calculations were transferred to the micro controller.

ESP32

One problem though with making the project PC-independent and mobile was, that the touch sensors started to get extremely inaccurate. This turned out to be caused by cutting the USB connection and causing a ground shift which will be discussed later in detail. To be able to still properly monitor the measurements and find the root of the problem a wireless connection was needed. The ESP32 offers Bluetooth and WiFi capabilities, which turned out vital to moving the prototyping forward. In the future, it will be vital for communicating with the app, which allows the plant's sounds to be exchanged, its species to be set or updates to be installed. The ESP32 offers a fast processor and a lot of functionality for an affordable price, so it became the final choice of micro controller.

Comparison of the three used boards:

	 ©Harrison Broadbent	 ©Vishnu Mohanan	 ©Hamed Taha
	Arduino Pro Mini	Raspberry Pi Pico	ESP32
CPU	8MHz	2x 133MHz	2x 240MHz
RAM	32KB	264kB	512kb
FLASH	2 KB	2MB	4MB
ADC	10bit	12bit	12bit
DAC	-	-	8bit
PWM	8bit	12bit	12bit
BT/WiFi	no	no	yes
Price	10€	5€	12€

In the future it may be a consideration to find a smaller and cheaper board with all necessary features. In order to reduce price and size, it might be reasonable to only use the microprocessor and not the entire board.

4.2 Environmental Sensors

There are three main components to determining whether the plant is doing well or not. Measuring the moisture in the soil is the most critical one, followed by temperature and exposure to sunlight.
To classify the health condition, the sensor data by itself is not enough though. Every plant needs its individual set of circumstances to thrive. Additionally, it is not enough to set a threshold above or beneath which these circumstances are violated. The time series of these computations is vital as well. For how long has the plant been arid? A cactus must not be watered at the very second that its soil dries up. The same goes for sunlight or temperature. The temperature fluctuates immensely throughout the day, ergo some form of averaging must be done at the very least. As this is a very specialized task, ample knowledge of flora is required. The current prototype implemented a fixed threshold.

Moisture Sensor

There are two major ways to measure moisture in the soil: Either via a resistive or a capacitive method:

Figure 3: capacitive sensor

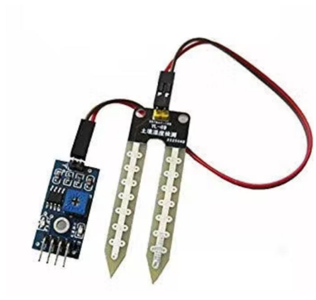


Figure 4: resistive sensor

The resistive moisture sensor

The resistive method works using a voltage divider with one fixed resistor and a variable resistance, made up of the soil between the two probes(see fig 4). The more water is in the soil, the smaller the resistance gets, which changes the ratio of the voltage divider. The problem with this approach is the corrosion of the probes. They are directly exposed to the soil which reduces the lifespan of the electrodes. Additionally, if there is a constant voltage applied, it causes electrolysis which in turn causes corrosion. Several possible solutions, like switching the polarity of the electrodes or measuring in sparse intervals, have been proposed. There really is no need to constantly apply voltage and measure several times a second when the moisture level changes far slower. Finally, with only a resistor and two electrodes needed, it is significantly cheaper to implement.

The capacitive moisture sensor

This sensor consists of two conductive copper plates which are insulated from each other and from the outside soil, so no electrolysis can occur. The sensor runs with a 555-timer chip putting out a square wave in the megahertz range. This square wave is then low pass filtered with a variable cut-off frequency caused by the changing capacitance between the two copper plates. This causes the RMS value of the signal to increase or decrease with a change in capacitance. The resulting output wave is then converted into a steady DC value that can be read from an ADC with a low sampling frequency.

The sensor works well and lasts longer than the resistive sensor but it is also significantly more expensive. It could be made without the 555-timer chip because the micro-controller can output such square waves itself. Since the cheaper approach works fine as well, the resistor-based sensor was chosen for the most recent prototype.

Light Sensor

Exposure to light is another crucial indicator for a plant to thrive. Or at least exposure to specific spectral regions of light. For this project a photoresistor was tested. It worked fine but there are several issues that need to be investigated to get a reasonable sensor which delivers meaningful readings for plants.

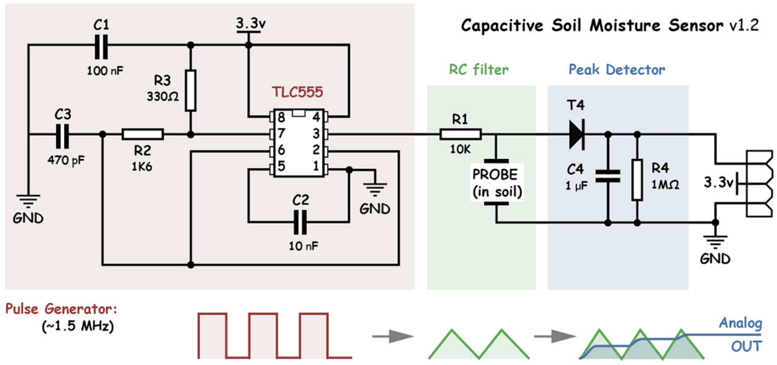


Figure 5: Circuit of the capacitive sensor

- Sensor placement & shadows:
  When using the photoelectric sensor, it was very easy to manipulate the readings by turning the planter around. It makes sense, that the sensor reacts to whether it is facing the window or not but it also shines light on a problem. To be able to derive a meaningful reading, it would probably be necessary to add multiple sensors on various positions around the device.
- Spectrum sunlight versus indoor lighting:
  Plants need a certain spectrum. Contrary to popular belief, the most important light for plant growth does not lie in the UV portion of the spectrum but in the visible light between 450 to 475 and 650 to 675 nanometers. Accordingly, it may not suffice to just measure intensity. A suggested solution might be, to filter out the less relevant wavelengths before they reach the sensor.

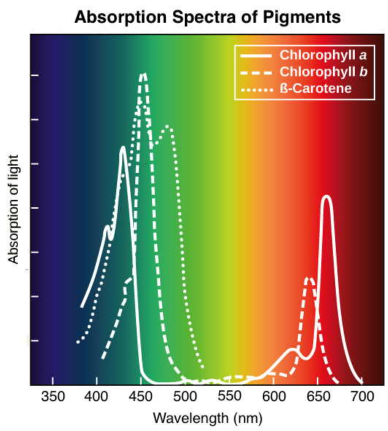


Figure 6: Absorbtion spectrum of plants

Making the moody plant energy independent is another important goal. In order to achieve this, it is planned to install a solar panel to charge the battery. If this is implemented, the light measurement might be included implicitly with the solar panel.

Temperature Sensor

As a final marker for the well-being of a plant we chose the temperature. The ESP32 has a temperature sensor integrated on-board. Its specifications state, that it can measure from $-40°C$ to $125°C$, which would be easily sufficient. Unfortunately there is a catch: There is an offset that is different for each chip due to process variations in production. This can be fixed by calibrating. The more problematic issue is, it is impacted by the heat, that the WiFi module gives off when used excessively. This problem might be fixed by time-averaging or only measuring when the WiFi-module has not been active most recently. Either way, for a meaningful reading, one would have to gain knowledge about the needs of specific plants. How long can they withstand high or low temperatures? When will a negative response exactly be triggered? Finally it should be considered, that it makes a difference whether the temperature sensor is placed inside the pot in the shade or if it is exposed to direct sunlight.

4.3 Audio-playback

The ESP32 has an 8 bit digital-to-analog converter integrated on the chip which can be used for audio playback. The quality, that an 8 bit DAC offers is quite poor though. In order to achieve a higher quality, an approach using pulse-width modulation (PWM) was examined. This technique uses a digital pin, that can only be set to either high or low, to

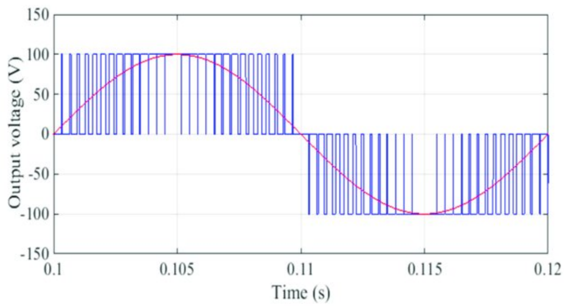


Figure 7: PWM signal and reconstructed analogue wave form [11]

create an analogue output. To achieve this, the PWM frequency needs to be significantly higher than the analog signal it tries to replicate. The amplitude of each audio sample is encoded in the duty cycle (ratio of high to low state within a cycle). When low pass filtered, the reconstructed analogue amplitude remains.

For this method a .wav-file was converted and uploaded to the ESP32 directly. The sound quality was acceptable but the memory on-chip is very limited. Since the idea of the moody plant is to convey many different emotions and not get repetitive, this is not acceptable.
To have access to sufficient memory and for easier handling of the playback, an MP3-audio-player module was purchased. This module includes an SD-card reader and it can be controlled using UART.

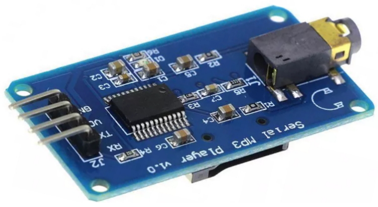


Figure 8: MP3-Audio-Player module with SD-card reader and aux-jack

Some of the UART instructions include volume control, choosing a specific file in a specific folder to play, sleep and wake up. The module includes an LED to signify if a sound is currently playing. Although this device sounds and works decent, it also has disadvantages. With all the included electronics and the aux-jack it is rather sizable. Additionally it cannot play overlapping sounds. If it gets triggered, it starts playing a new sample unless you block it from triggering for the duration of the audio sample. The audio playback with overlapping sounds was tested on a Pure Data patch and the feeling was a lot more interactive, interesting and natural. As of yet this module is the implementation for audio playback. Another consideration would be to buy a separate SD-card reader and using the PWM approach or to invest in a dedicated external DAC with higher resolution.
Eventually the analog audio signal was amplified with an OP-amp circuit using a LM386

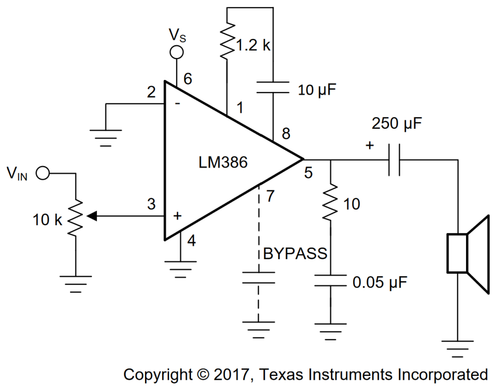


Figure 9: LM386-Amplifier circuit with gain = 50

[fig. 9] with a circuit resulting in a gain of 50. This operational amplifier can be driven with the supply voltage of 5V that we also use for running the ESP32. The output is connected to a small dynamic speaker. A cardboard speaker enclosure was built to avoid an acoustic short circuit and to move the cut-off frequency on the low end further down.

4.4 Battery-management

Starting out, the project was USB powered. Ultimately the goal was to create an installation that looked like a regular flower pot. Consequently, in a second iteration, a battery powered version of the ’moody plant’ was attempted. Due to a lack of a 5V or 3.3V battery, 9V batteries with a linear voltage regulator were chosen for the setup. For the voltage regulator an LM7805 chip was used to get the 9 volts converted to a constant 5 volts, which could power the ESP32 board and peripheral electronics. It is a cheap device that is easy to set up. With only two additional capacitors a stable voltage source is created

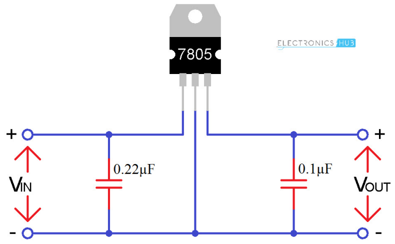


Figure 10: Linear voltage regulator 7805 with 5V output

Linear voltage regulators are not very efficient though. Much of the battery's energy is dissipated as heat. Consequently, several batteries were drained during prototyping. A buck-converter would be a possible alternative. It is more efficient but it is also more expensive and causes a magnetic field which can interfere with the circuitry as well. In the end an entire battery shield with a rechargeable 3.7V Li-Ion battery was chosen. This shield can be used to charge the battery with a micro USB cable, even while powering the micro-controller. Next to the charger, it offers under-voltage protection, a boost converter as well as a low dropout regulator so it can output 5V as well as 3.3V. Unfortunately the boost converter is always active and discharges the battery even without load. The battery life remains a problem. In order to extend the lifespan, it was suggested that a solar panel could be added.

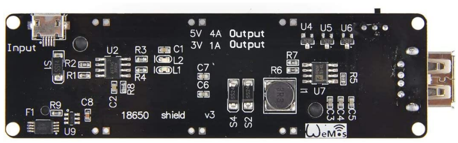


Figure 11: ARCELI Wemos 18650 Battery Shield V3

4.5 Touch-sensing

The crucial innovation of the 'moody plant' consists of the possibility to make any household plant, that you put inside the pot, touch sensitive. This tactile, natural and very responsive way of interaction gives the perception of a live creature with feelings and needs. To enable such interactions, a custom capacitive sensor was developed.

In general, a capacitor consists of two electrodes that are separated by a non-conductive dielectric. The capacitance depends on the size of the electrodes, the distance between them and the dielectric constant of the material in between. In this case, material between the electrodes is made up of air and won't change. The surface and distance of the electrodes however can be influenced by touching the plant. Basically, the circuit, the plant, and the person touching the plant create a big capacitor.

Capacitive sensing can generally be divided into active and passive variants. In active sensing, a signal is applied to the transmitter electrode, which is coupled into the human body, and the receiver electrode. By monitoring the strength of the coupling, the presence or absence of the body can be established. Much of existing literature is focused on this approach. Passive touch sensing relies on existing electric fields, that are - through the body - coupled into the receiver electrode. Power lines and electronic devices can be such external fields[3]. In a first iteration, it was attempted to implement such a sensing approach. It turned out to be very dependent on the surroundings and not robust enough. Small changes, like wearing plastic slippers or sitting instead of standing, made huge differences in the measurements.

Furthermore, the sensing approach can be divided into four modes depending on the distance between electrodes and the interacting person. The plant itself was chosen to be the transmitter electrode, so a touch on the transmitter side should be detected. This corresponds to the 'transmit mode' in fig. 12. In this mode, the interacting person acts as extension of the transmitter. They are coupled significantly stronger to the transmitter side than to the receiver electrode or the electrodes are to each other.

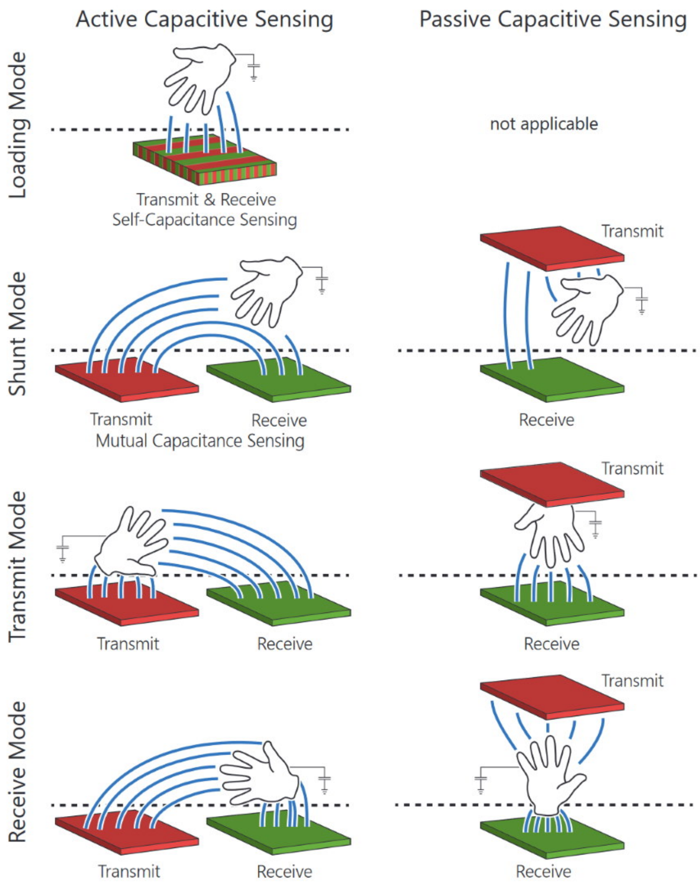


Figure 12: Capacitive sensing techniques can be divided into four operating modes: loading, shunt, transmit and receive. Except for loading mode, each mode may be implemented using active or passive sensing. The dashed line represents the boundary between the sensing system (bottom) and the environment (top) [3]

The variability of plants and surroundings makes it very difficult to detect every interaction reliably while trying to avoid premature triggering. The sensor is inserted from below into the soil of the plant. Changes that can be measured when touched are very small and the electromagnetic noise, picked up by the sensor, cannot be neglected. With automatic adaptation to surroundings and plant size the robustness of the detection can be improved greatly. Over the duration of the project, various approaches have been tested.

Magnitude response measurements

Starting out, the micro-controller that was used was the Arduino Pro Mini and was connected to the PC via USB. Over a $10M\Omega$ resistor a 100Hz Square wave signal was output and then connected to the soil of the plant. The voltage was measured at the junction between the resistor and the plant. The sampling frequency of the ADC was set to a multiple of the digital output signal to capture more than just the fundamental frequency. After being converted to a digital signal and low-pass filtered, the RMS value was computed. Trying to avoid high variance measurements, the RMS value was calculated over multiple periods of the 100Hz signal. On the other hand, the readings should still be responsive and avoid a noticeable delay. For this reason an significant overlap was chosen. This enabled meaningful readings from the sensor 20-50 times per second, depending on exact sampling frequency and overlap.

The calculated RMS value was then sent over USB and fed into a Pure Data patch where it was further processed. The Pd patch can be divided into several sub-tasks:

- Calibration
  The base signal power strongly depends on the inserted plant. The base impedance strongly varies with size, shape and number of leaves. Additionally, the surroundings influence the baseline behaviour significantly. If there are many electrical devices near the planter, the base level and also the variance change significantly. To allow for changes a calibration mechanism was included. For the adaptation, the program instructs you to

  - stay away at least 2 meters
  - stand close to the plant
  - slightly touch a leave with 1-2 fingers
  - touch many leaves at once

  for several seconds each. From these calibration measurements, thresholds are calculated to differentiate between baseline, proximity, or touch. In this version, sounds were triggered as well when someone was just walking by in close proximity.

- USB input parsing
  Depending on the computer, the correct USB input port needed to be chosen and the incoming bytes needed to be converted from ASCII values. In addition to the sensor values, a prefix was transmitted to differentiate between different sensors. This could be moisture, light, temperature or touch and was routed accordingly in Pd.

- Signal monitoring & classification
  The calibration has already set a baseline for detecting touch and proximity. The found thresholds are not one hundred percent accurate and need to be adjusted occasionally. To do this, there are two tables (bottom in fig. 13) that display a rolling time series of the sensor data overlaid with the threshold constants. This way, the decision process can be visually analysed. On the right side of the patch, it displays which of the three modes was detected at the moment.

- decision tree for mood and audio playback
  For this iteration, there were three different moods available: happy, angry and needy. Next to the current sensor values, the recent history was taken into account as well. The plant had a short term memory so to speak. When not touched for

a while it became needy, if touched for too long, it got angry. To avoid triggering a sound every time the sensor detected a touch, which could be up to 50 times a second, the audio playback was then blocked for a certain amount of time. The amount was either fixed or playback was blocked for as long the last audio sample lasted. The fixed time variant allowed for overlapping sounds which created the impression as if every leaf had its own voice and personality and made it more lively.

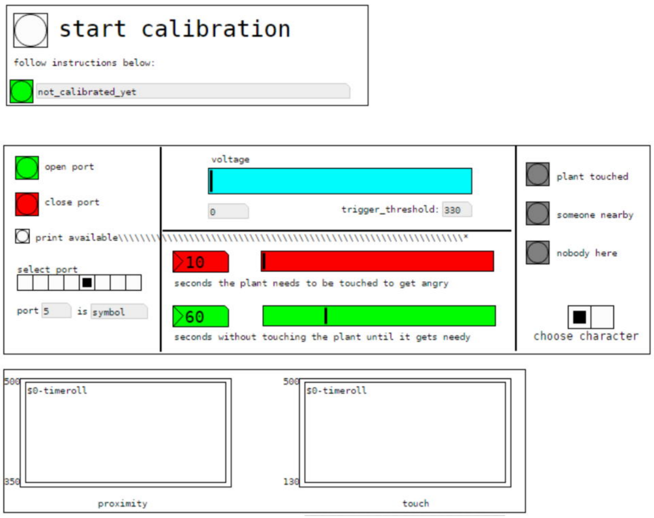


Figure 13: Pure Data patch for debugging, analysis and audio playback

Ground Shift Problem

The idea was always to be independent from any processing on a PC, so it was attempted to move all components to the micro controller. While battery management and audio-playback needed to be resolved as well, it was the touch-sensing which suffered the most when removing the USB connection.

"*The role of ground is also important - it simply refers to a common potential to which all of the objects relevant to the system are electrically coupled. Without this common ground, capacitive sensing systems do not have a shared reference, which is critical to operation in many cases.[3]*"

When powered by a battery, it was impossible to detect differences when the plant was touched. As an explanation the lack of a common ground can be given. As long the micro-controller is connected to the power grid via USB, the circuit ground and the system ground are both referenced to earth ground. As soon as it is disconnected, the circuit is now referenced to a local ground which is weakly coupled with a parasitic capacitance C_g to the system's earth ground[5].

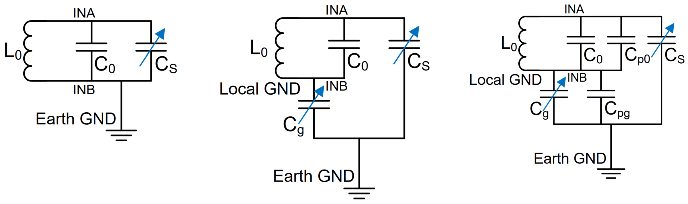


Figure 14: Simplified Model of the FDC2214 EVM Board with common earth ground (left), local and earth ground (middle), added large ground plane to increase the coupling between local and earth ground [5]

To compensate for the ground shift, a larger ground plane/electrode can be introduced as a receiver. In this case, an aluminium foil electrode was connected to the micro-controller's ground. Another proposed solution would be to greatly increase the input impedance[3][5].

Botanicus Interacticus and Swept Frequency Touch Sensing

As there were still major problems with sensing touch when the micro-controller was disconnected from the power grid, more research was done. With 'Botanicus Interacticus'[7], a very similar project has been done. It uses the concept of frequency swept capcitive sensing[9]. This approach uses a frequency sweep, ranging from 1 KHz to 3.5 MHz. After low- and high pass filtering and amplification, the sweep signal is connected to the object that is being touched. The resulting change in signal level depends on the impedance which in turn depends on the output frequency. Because the ADC would be way too slow for such high frequencies, the signal is passed through an envelope detector to capture the signal level.

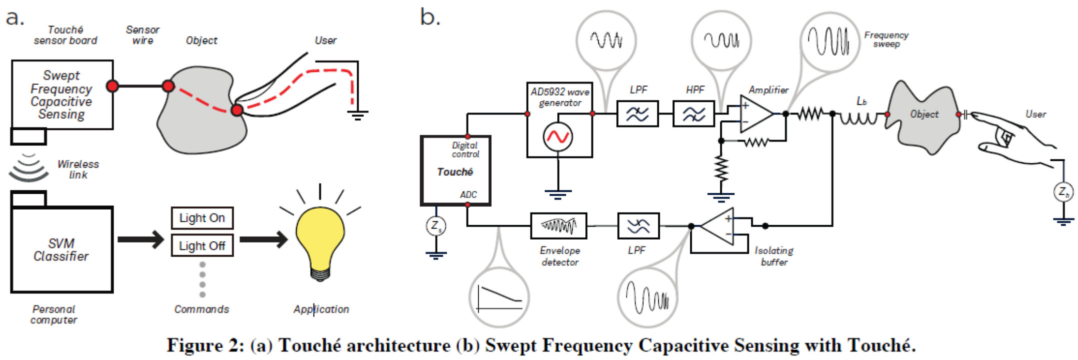
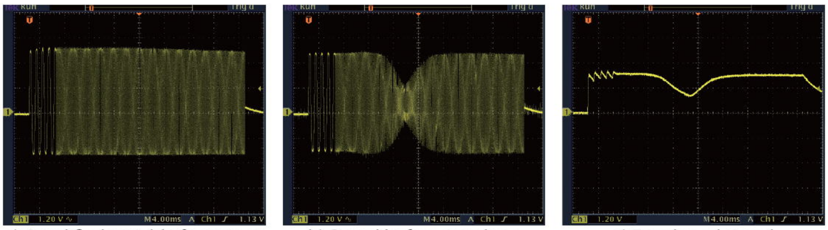


Figure 15: Schematic of the Swept Frequency Touch Sensing approach[9]

With this approach, you gain information about the entire transfer function over a large frequency range. Using machine learning, support vector machines in this case, not only can the touch be detected but also differentiation between gestures (light touch, strong grip, etc.) can be made.

This setup was attempted but due to a lack of exact documentation and a lack of an oscilloscope at the time it failed. The envelope detector did not seem to work, so it was attempted to get the ADC to work at higher speeds with the help of the I2S protocol. The results were not great. A frequency analysis showed that the majority of changes caused by a touch were in the 50Hz range of the power grid. If the circuit was moved away from the power grid, the sensitivity dropped to an unacceptable level. It needs to be said, that the frequency range was still significantly lower than the one used in [9] and that in the paper, the circuit was probably still connected to the power grid.



a) Amplified variable frequency sinusoidal signal b) Signal before envelope c) Enveloped signal

Figure 16: Frequency sweep and return signal[9]

Although this setup did not work out for this project, there likely still is a lot of potential in the idea of frequency swept touch sensing that needs to be explored.

Relaxation oscillator

Going away from the approach of measuring changes in signal amplitude, we are now trying to measure changes in capacitance through a change in the time constant. The setup used is basically an RC-circuit. The time constant, which represents how fast the capacitor will be charged, can generally be calculated as:

$$\tau = RC = \frac{1}{2\pi f_c} \tag{1}$$

Of course, this is extremely simplified since the human body, the plant and the air cannot be expressed as a single capacitance. Still it makes sense to look at the problem like this. We can detect changes in charging time when we touch the plant. Since we are dealing with a very low capacitance, the resulting (dis-)charging time is fairly short. Accurately measuring the moment at which the voltage passes the threshold becomes difficult, especially when the signal has a bad signal to noise ratio.
As a next step we introduce the relaxation oscillator. This oscillator uses an operational amplifier to generate a square wave signal. The frequency depends on the RC circuit that is connected to the OP-amp.

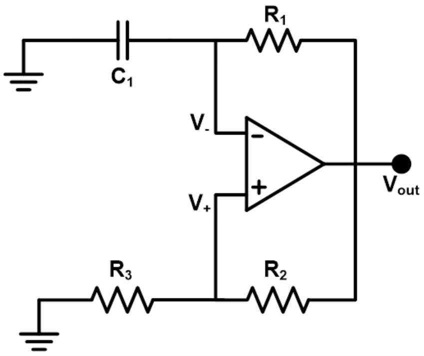


Figure 17: Relaxation oscillator circuit using an OP-amp

When the output of the OP-amp drives the circuit with the positive source voltage, its non-inverting input voltage is determined by the voltage divider of R2 and R3. Assuming $R_2 = R_3 = R$, it results in $\frac{V_s+}{2}$. The RC-circuit connected to the inverting input of the OP-amp is then being charged until the voltage across the capacitor is higher than at the non-inverting input. The time constant again determines how fast it will charge. When this threshold is surpassed, the voltage difference between the OP-amp inputs changes sign and it will output the negative source voltage. The resistive voltage divider determines the voltage at the non-inverting input and the discharging of the capacitor begins until its voltage drops below this threshold. This circuit keeps charging and discharging indefinitely, which results in a square wave signal being output at a frequency determined by the capacitor.

$$f = \frac{1}{T} = \frac{1}{2 \cdot R_1 C \cdot ln(1 + \frac{2 \cdot R_2}{R_3})} \tag{2}$$

The ratio of the resistors that form the voltage divider, determine the threshold at which voltage the polarity changes. This is called a Schmitt Trigger and it provides hysteresis behaviour. This means that there are two different threshold levels for rising or falling flank of the signal. Without hysteresis it would mean, that with a noisy input signal around the single threshold, the output of the OP-amp would rapidly fluctuate between positive and negative voltage supply.

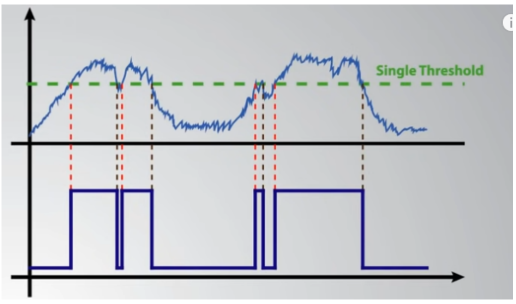


Figure 18: Without Schmitt Trigger

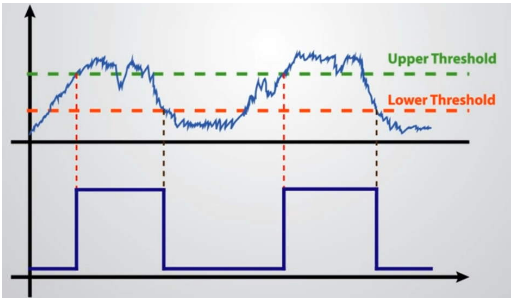


Figure 19: With Schmitt Trigger

To measure the frequency of the relaxation oscillator, external interrupts were used, counting up each rising or falling flank. Using external interrupts with a counter is rather easy on the CPU and it implicitly averages over many cycles. Ergo fluctuations, that are caused by noise and other factors, have a significantly lower impact. During tests, a frequency around 10kHz was measured. Reading out the counter and resetting it 20 times a second, results in a very quick response time while also averaging over 500 charge and discharge cycles for a robust measurement.

An extremely helpful tool for prototyping was the oscilloscope, that was finally acquired. Unfortunately it still induces an external capacitance just by connecting it to the circuit for measurements. Connecting or disconnecting the oscilloscope resulted in differences in frequency of around 2kHz, which is quite significant with a base frequency of around 10kHz. So in conclusion, this technique is the most reliable and responsive so far while also not being very computationally expensive. A different environment, plant or other small changes can still lead to large variations in frequency. In order to be more robust, even when parameters change, automatic adaptation was implemented in code.

Side note - moisture sensor: The touch detection measurements rely on a signal being applied to the plant soil. This signal is captured by the moisture sensor as well. In former implementation, this was solved by pausing the touch measurements, meaning the output pin of the sensor, that was not being used, was changed to a high impedance input pin. The relaxation oscillator emits the signal directly, so it can not as easily be suppressed.
Side note - integrated touch sensor of the ESP32: The ESP32 comes with native touch sensitive pins. It was attempted to use the integrated sensors. Directly detecting a touch on a wire or foil connected to these pins worked perfectly. When connecting with the a plant though, it was impossible to reliably recognize a touch.

4.6 Software

The most important software aspect was to make the touch detection adaptable to different surroundings and varying plants. 20 times a second, the counter connected to the relaxation oscillator was read out and reset to 0. From the counter value, the underlying frequency was calculated and the resulting value was pushed into a circular buffer. This buffer was used to save frequency measurements of the past 10 seconds. 10 seconds times 20 measurements per second add up to a 200 samples long buffer. When the micro-controller is started up for the first time, it waits until this buffer is filled and then sets a base level according to the mean of the buffer. The threshold of when a change in frequency is interpreted as a touch is set depending on the variance within the buffer. If this threshold is crossed, a sample is played. During the playback no more touches can be detected and no new sound can be triggered.
As long as the plant is occasionally being touched, the values in the buffer have a significant variance. When this variance decreases and there are no significant changes over the 10 second period represented by the buffer, it means, that it is no longer being interacted with. At this point in time, we can start to slowly adjust the base level of the touch detection towards the current mean of the circular buffer. If the plant is being moved elsewhere,

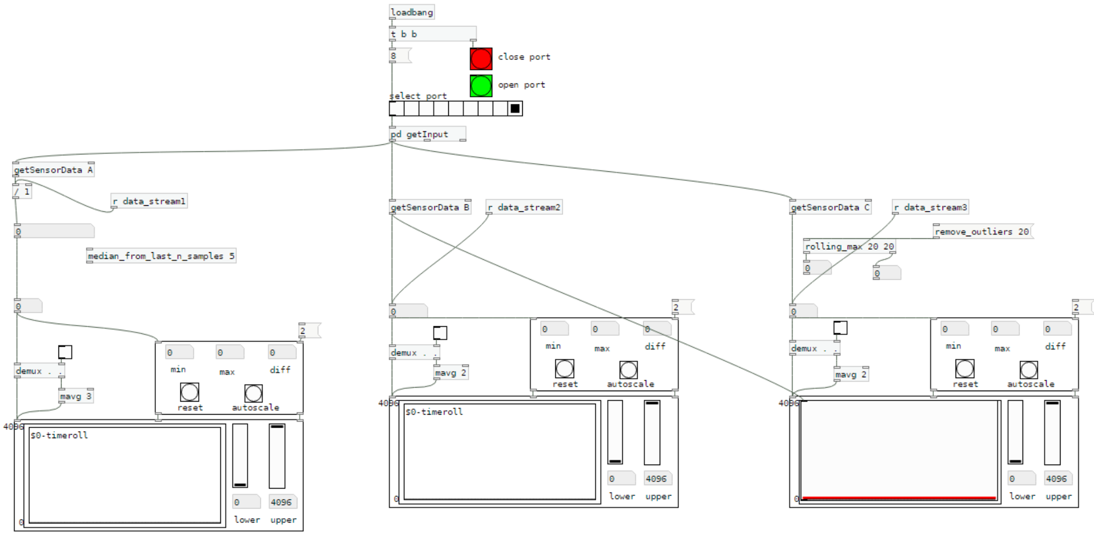


Figure 20: Newest Pure Data patch for Udp monitoring, debugging and data processing

the base level (average frequency, when the plant is not being interacted with) changes. This can for example be caused by closer proximity to electric appliances. At first it is impossible to detect when it is being touched. But when you leave it alone for 10 seconds it start adapting to its new surroundings and a new base level is set.

For debugging and monitoring purposes, a Pure Data patch has been used. Since there no longer is a USB connection to send debug messages, wireless UDP communication was implemented. The ESP32 was connected to the WiFi and was able to broadcast the raw frequency measurements and other messages. Additionally, values like the variance, at which we would start adapting the base level, could be changed from within Pd. Some further signal processing was applied to get an even more robust detection. Averages, medians and maxima from the last n samples were used and outliers were rejected. Some improvements could be determined but using more averaging techniques also meant a slower reaction time of the system.

Figure 21: Final Moody Plant flower pot with integrated circuitry

4.7 Chassis and final product

For the final product, a flower pot was 3D printed. The pot has a hole through which the sensors can be inserted into the soil. It was designed with an empty space below the plant in which all of the electronics can be inserted. Finally it got acoustic ventilation openings because the speaker would be placed within the enclosure below as well. The vents were designed to display a sinusoidal wave. To give the talking plant a more lively appearance, facial features such as eyes and a mouth were drawn onto the flower pot.

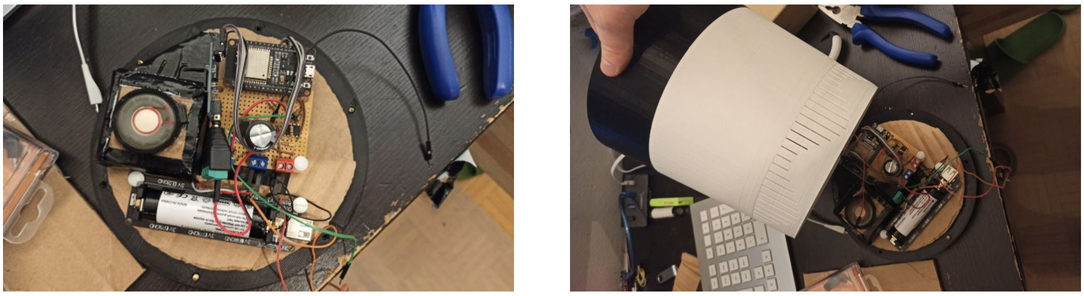


Figure 22: Final Circuit

5 Accelerator program and reception

When the first prototype showed promise, the moody plant was also submitted for a spot in the accelerator program 'Gründungsgarage'. This accelerator is a university-related support program for students that want to found a start-up. After a first presentation in front of a jury, the project was accepted to participate in the semester-long program. This meant weekly workshops and tasks, mostly concerning the non-technical side of a start-up. Up to 10 teams participate in these workshops each semester, learning about business models, online marketing, intellectual property rights, taxes and legal forms of a company, branding, pitching, raising money and much more. Outside of these seminars, the projects were further supported by experts with various specializations from economy and academia. After the program, in the final pitching event, the teams could win prizes depending on how well their project was perceived by the crowd and the jury.

Business Model

With the business model canvas a starting point was created, on which an overview over all aspects of the business and the product is given. It was updated throughout the semester which also led to changes in the prototype goals.

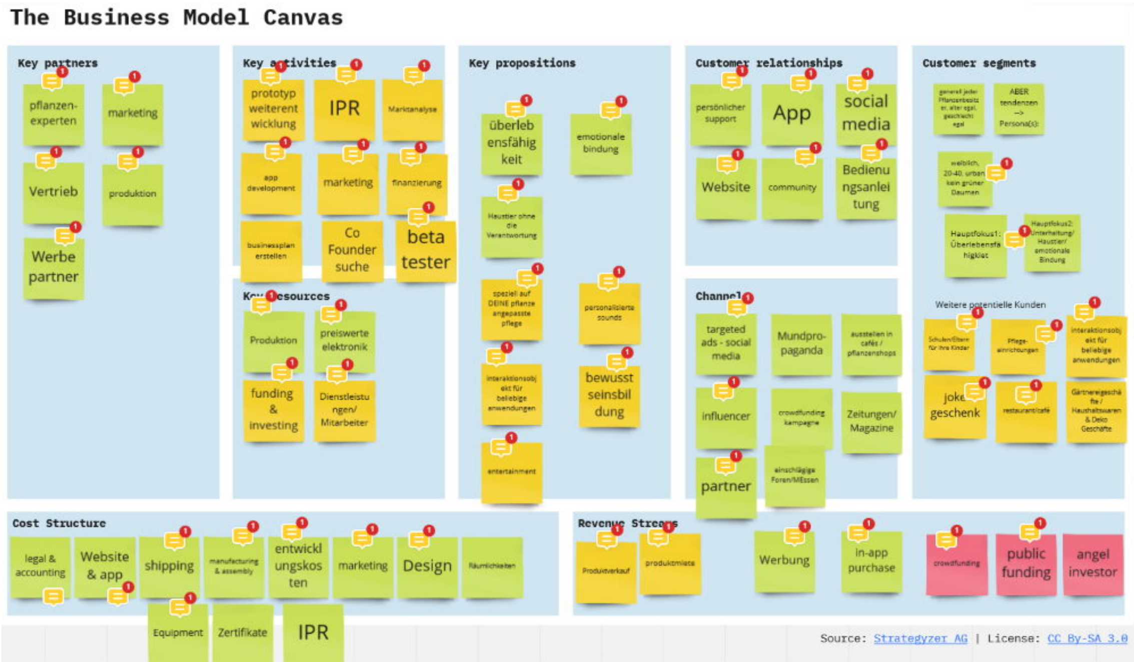


Figure 23: Business model canvas

The key propositions section represents the unique value or combination of values that only your product can offer. A major benefit is that the 'moody plant' gives life to your plant and thus creates an emotional connection and a sense of responsibility like with a pet or the Tamagotchi. As a result it is supposed to increase the plants lifespan through the increased interaction. Aside from that it can also be used to create awareness for nature by giving it a voice. This might be used for educational purposes.

In discussions with the Gründungsgare community several features were highly requested. The possibility of running it on battery and not needing to connect the flower pot to an external power supply was an important feature. Another called for feature was the capability to use an app to adjust the algorithm to a specific plant, to download new sounds or explicitly look at the sensor data. When it came to analysing possible income sources it became clear, that an app would also benefit the profit margin. If the app could be used to get small transactions for new sounds for example, the original product could be produced at a higher price resulting in higher quality. This is also why the price of different hardware parts was always kept in mind during prototyping. In the end, this feedback was the reason why the 'moody plant' was turned to a battery powered system and why the WiFi capable ESP32 was chosen as a micro-controller.

In the channels section, the app is also mentioned but so is a website. Through the website people could subscribe to a newsletter and stay up to date. They could get in contact to share ideas, collaborate or share the project. It is used as a landing page to lead people to other channels, like the social media accounts that have been created as well. Finally it gives credibility to the project, also by referencing its appearance at the accelerator program. The website (see 24) was made using 'WordPress' and 'Elementor', the mailing lists were managed using 'mail-chimp'.

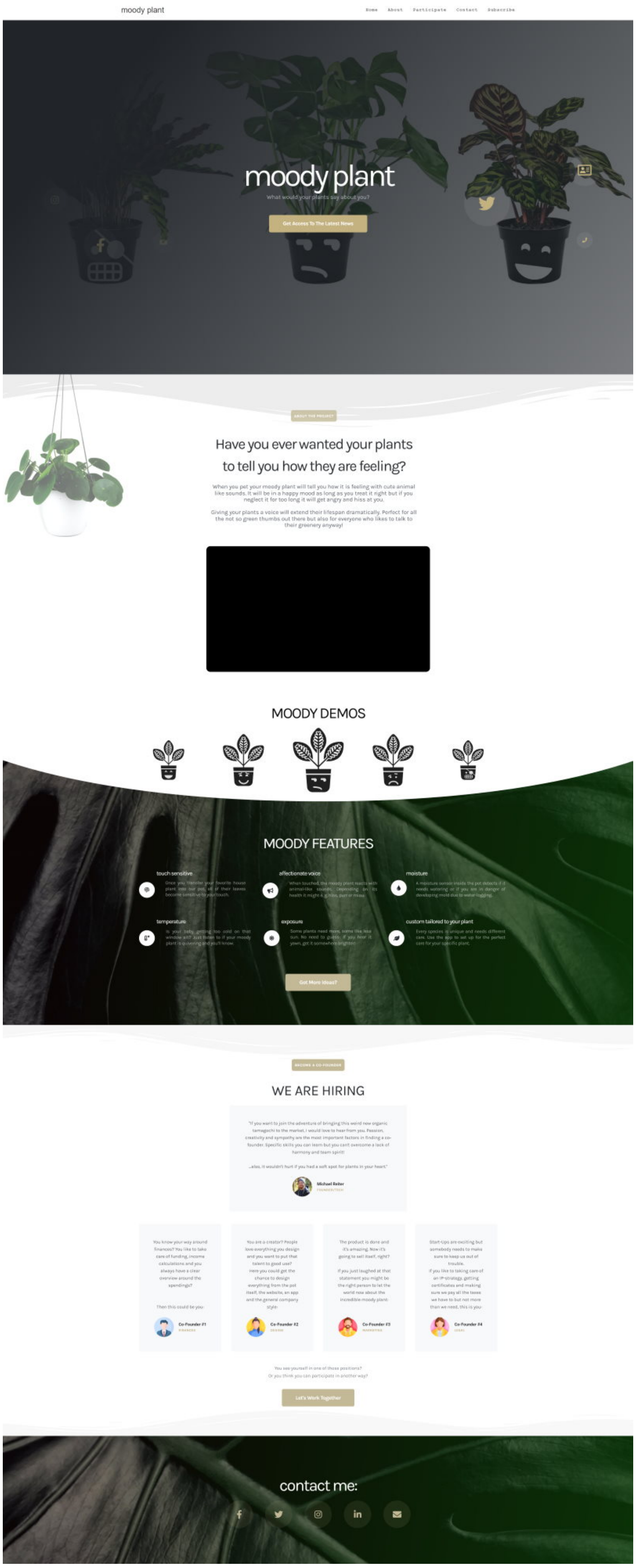


Figure 24: Website: www.moody-plant.com

Feedback

Supported by a coach, a presentation was created for the pitching finale. Within 3 minutes the concept of the product, the business concept and future plans were presented and broadcast live over a streaming platform.

Via an online feedback and voting tool each team was graded and additional questions could be asked by the crowd. In the end the 'moody plant'-project won the vote and with it several prizes.

Figure 25: Streamed presentation

Figure 26: Award ceremony

Figure 27: Presentation at the final pitching event at the Gründungsgarage

The feedback from this appearance was overwhelmingly positive and the audience was very intrigued by the technology. Several people offered support or cooperation afterwards and the 'moody plant' later also appeared at the 'Gründermesse' in the 'Messe Graz' and was mentioned in several news outlets (Kleine Zeitung, Steirisches Wirtschaftskammer Blatt, Tipps, Steinhauser Gemeindezeitung, TU Graz Website)

Written feedback from the audience after the presentation:

- enormes Potenzial
- Spaß als Hook wichtig, Funktionalität als zusätzlicher Benefit
- Sympathischer Pitch. Gute Weiterentwicklung.
- Präsentation kreativ designt. Call for Action war sinnvoll.
- Du bist ein großartiger Typ, deine authentische Art trägt deinen Pitch und das Projekt. Wenn du es noch schaffst, im Pitch und Slide Deck ein wenig schneller auf die wesentlichen Punkte zu kommen, dann steht einem nachhaltigen Erfolg von Sales Seite her nichts im Weg, bin ich mir sicher. Weiter so, super!
- auch wenn deine Ziele laut Zielvereinbarung nicht zu 100% erreicht wurden, finde ich, dass du einen steilen Fortschritt hingelegt hast. Weiter so.
- super Weiterentwicklung bei Business Präsentation (Inhalte, Sturktur, Auftreten) ersichtlich. Gratulation, gut gemacht! finde ich einfach spannend. Dran bleiben und die GG kann beim Co-Founder Matching sicher helfen.

- Kaufe ich sofort! Bin eher für Spaß Faktor :)

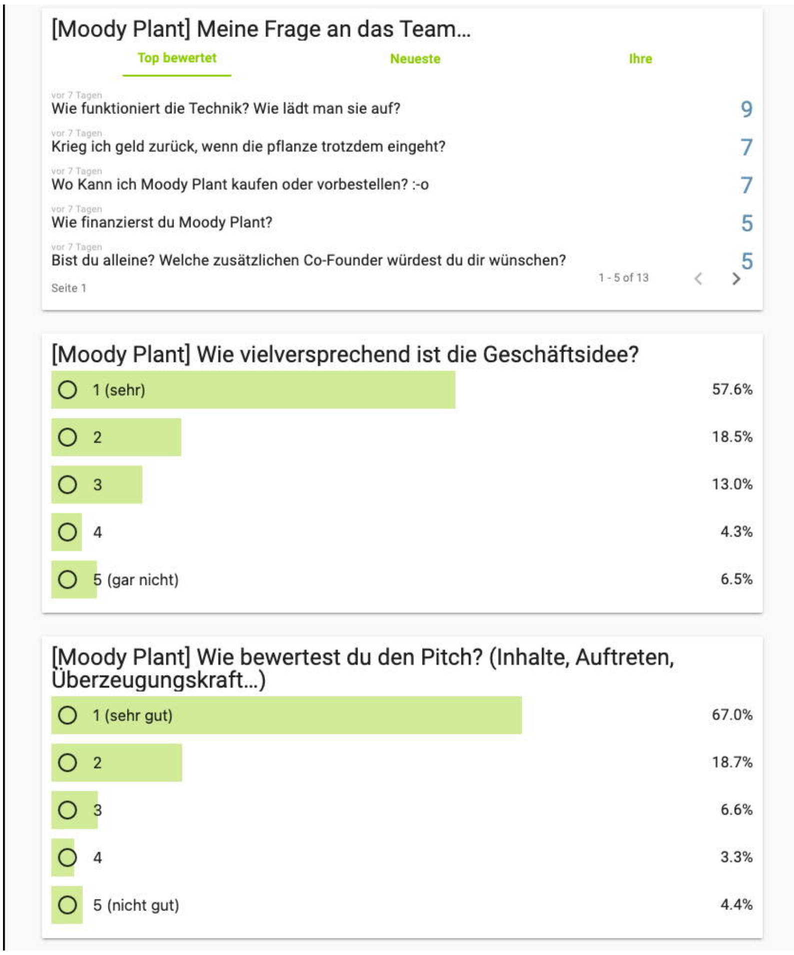


Figure 28: Feedback after the presentation via online tool

6 Conclusion and outlook

So far there have been many iterations in every aspect of the hard- and software. Some work better, some are easier to implement, some are cheaper. Due to the complexity, some aspects have been neglected while prototyping a different idea. This is why not all hardware was implemented in an optimal way in the final product. The most important part, the touch detection when brushing over the plants leaves, works well enough. The feedback of people watching the presentation or interacting with the plant themselves was overwhelmingly positive. Giving plants a voice, giving them live and making them interactive is something people really seem to enjoy. Additionally many people claimed that they really needed such a device to prolong their plants' lives.

There is still a lot of problems that need to be solved and improved upon. The hardware needs to be optimized and made more cost- and energy-efficient. An app to interact with the micro-controller to adapt to different plants needs to be developed. The sensors that determine the plant's health need to be fully implemented in the prototype and algorithms to interpret these values need to be worked out. This would require the knowledge of a botanical expert. Installing a solar panel might greatly increase the time until the battery needs to be recharged. When the temperature, moisture and light sensors all work properly, enough new sounds, representing all kinds of combinations of states, need to be recorded. Afterwards they need to be tested to see if users will intuitively interpret the sounds the way they were intended to. The touch detection generally works rather reliably but can definitely still be improved upon.

As of now the project has been frozen due to lack of time but might soon be continued, possibly with the help of some of the people who showed interest in doing so.

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