Plantxel: Towards a Plant-based Controllable Display

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Figure 1. A conceptual plant-based display with multiple plants as pixels (plant-pixels or *plantxels*) that close their leaves based on external stimuli (e.g. vibrations, touch, air flows, or electrical signals). The conceptual display is obtained by reproducing and arranging a single plantxel made of a *Mimosa spegazzinii* plant in its normal state (open leaves - darker green pixels) and when exposed to an air flow (closed leaves - revealing the white background). The plantxel is controlled by a prototype system developed to control the air flow from an air source to the plantxel as shown on the right.

ABSTRACT
The use of plants as a mean for both visualization and interaction has been already explored in smart environments. In this work, we explore the possibility of constructing a controllable dynamic plant-based display using thigmonastic plants, i.e. plants that change the shape and position of their leaves as a response to external stimuli. As an initial step towards this vision, we first introduce our approach of building a plant-based pixel (plant-pixel, or *plantxel*), and the principles of composing a plantxel-based public display. We then present the results of a feasibility study conducted with *Mimosa spegazzinii* plants, showing that our approach can achieve an acceptable contrast ratio, which in turn depends on leaves density. Based on the results of the study, we present a working prototype of a plantxel that is composed of a plant, the air-based stimulation system, and the control logic. The prototype allowed us to assess the effectiveness of our design choices, and to outline some potential limitations. Finally, we discuss the possibilities of using such plant-based display for dynamic information visualization in public spaces and provide directions for future work.

ACM Classification Keywords
H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

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Public displays; plant-based displays; concept prototype; information visualization; thigmonasty.

INTRODUCTION
Public displays are a common way of conveying information in public spaces. In addition to traditional signage and digital displays, there are also many examples of plant-based landscape displays. The most prominent examples of such displays are floral clocks and artistic installations in public parks. These displays are based on a precise arrangement of heterogeneous plants with flowers of different colors in predefined grids that, when observed from a distance, portray a static image or convey a particular message to the public.

Floral and plant-based displays are not new, but they are mostly static. The position of the plants and their arrangement stay the same throughout the installation period and the message they depict is usually the same. However, as early as in mid eighteen century, scientists already envisioned advanced floral displays that can dynamically change based on the context and external stimuli. For example, Carl Linnaeus proposed a floral clock that can change during the day by opening and closing flowers to precisely indicate the time [18]. In addition to the sensitivity to light, there are groups of plants that are sensitive to other external stimuli, such as touch and vibration. This property is known as *thigmonasty* (or *seismonasty*) [24]. Two common (and very similar) plants that exhibit thigmonasty property are *Mimosa pudica* (also known informally as "shameplant") [1, 17] and *Mimosa spegazzinii* [23].

In this work, we propose a conceptual model of a dynamic plant-based display consisting of multiple plants as individual display pixels that can change the position of their leaves by exploiting the thigmonastic property. In particular, we focus on using *Mimosa spegazzinii* plants that react to direct air flows by closing their leaves. We present a feasibility study, with 12 different *Mimosa spegazzinii* plants, evaluating the perceived color difference (contrast ratio) between the plant with open leaves (normal state of the plant) and the same plant with closed leaves after being exposed to the stimuli, thus revealing whether the changes of a plantxel can be perceived by the human eye. With the positive results of the study, we implemented a prototype system of a plantxel using Raspberry Pi and a solenoid valve that control the exposure of the plant to an air flow. Finally, we present our first experience with the prototype system, discuss how to use plantxels to build dynamic plant-based displays as illustrated in Figure 1, and outline limitations and possibilities for future work.

RELATED WORK

A wide range of hardware has been used and studied in order to design public displays [6]. Starting from the split-flap displays used in early public signage [3], nowadays the majority of public displays are based on LCD hardware and cover various form factors. Along with traditional LCD solutions, researchers experimented with new forms of emerging display hardware. For instance, projected displays have been more and more deployed and used in the last few years [11], allowing for displays of various shapes and sizes [27, 2]. As a further step towards new forms of displays, Nakagaki et al. developed Materiable [20], a shape-changing display able to render dynamic material properties by moving a single pixel. Furthermore, Williamson et al. developed Levitate [26], a levitating particle display based on ultrasounds.

In relation with the content of this paper, and still in the context of emerging display hardware, it is worth mentioning that the use of plants for building novel displays has been already explored. Floral clocks and similar installations in public parks are probably the most simple and common plant-based static displays. They used heterogeneous plants with flowers of different colors in order to combine them into a big static image, usually visible from distance. While such idea is quite diffused, the main limitation of floral clocks is that they are not dynamic. Another famous form of plant-based static displays are the well-known crop circles. Although obscure natural causes or alien origins of such circles have often been suggested by fringe theorists, all crop circles are consistent with human causation. Andrew Glassner defined them as "the coolest display medium for computer graphics", and discussed about how to create crop circles in [10]. Interestingly, crop circles have been made also for advertisement purposes (see for instance [19]). However, their main disadvantages consist in the static nature of crops, the difficulties to overcome in order to create such circles, and the impossibility of reusing crop circles after having designed it (e.g. in order to change the displayed figure).

Flower-based displays have also been studied in order to create dynamic solutions. In 1751, Carl Linnaeus theorized a particular floral clock that would take advantage of several plants that open or close their flowers at particular times of the day to accurately indicate the time [18]. While Linnaeus may never have implemented such idea, several botanical gardens in the early 19th century attempted to deploy such plant-based display, with mixed success. This can be considered the first attempt towards a dynamic plant-based display, although non-controllable and very difficult and expensive to implement.

Although in this paper we focus on the use of computers in order to control plants, it is worth noting that previous work has also investigated how to use plants for user interaction. For instance, Poupyrev et al. developed Botanicus Interacticus [21], a system aimed at recognizing which part of the plant is touched by a user and making and appropriate interactivity event. Moreover, Kuribayashi et al. developed a more generic toolkit aimed at developing human-plant interactions, named I/O Plant [15]. Finally, more complex attempts have consisted in making plants able to "move" themselves by means of a flowerpot-type robot called PotPet [13]. While we do not focus our work on interactions through plants (our goal is to make a dynamic but non-interactive plantxel), such idea may be of great interest for future work (e.g. in order to develop interactive plant-based display).

Considering more prominent plant-based displays, Kuribayashi and Wakita developed PlantDisplay [16], which allows users to control light and water supply for plants. This represented a first attempt towards computer-mediated interaction with plants and developing a plant-based ambient display. More recently, Kimura and Kakehi developed MOSS-xels [14], which uses blocks of a species of moss called *Racomitrium canescens* as pixels. Such plant can change its state (and so its appearance) by absorbing water, which in turn can be controlled by an automatic watering system. While this solution has the advantage of being dynamic, its main downside is that the different appearance of dry and wet moss (contrast ratio) is not so evident, representing a potential limitation in terms of feasibility as a general purpose display. Moreover, every pixel needs from 5 to 60 minutes to change its state.

The use of thigmonasty to control plants has also been explored by several researchers. Kurihara et al. implemented an Arduino-based control system for closing leaves of *Mimosa pudica*, named Botanical Puppet [17], by exploiting the response to electrical stimuli (described by Volkov et al. [25]). This would allow to consider two interchangeable states of a single plant (i.e. open leaves and closed leaves), making it mappable to a boolean function [7]. While Botanical Puppet represents a first attempt to exploit thigmonasty in order to control plants by means of computers, to our knowledge, there have been no attempts to exploit such plant behavior with the specific goal of building a basic display element for larger dynamic plant-based displays. Also, in contrast to Botanical Puppet that requires invasive electrodes attached to a plant and sending electrical signals through the plant, we use air flow to stimulate plants and close their leaves, resulting in a system that is less invasive but equally effective.

THE PLANTXEL CONCEPT

As previously mentioned, it is possible to control plants that show thigmonasty by means of external stimuli. This would allow for implementing a dynamic plant-based display using multiple thigmonastic plants. The elemental controllable part of such display, which would correspond to a “pixel” in a common display, is what we call a *plantxel*, meaning that it is the plant-based picture element. A plantxel is thus a group of one or more leaves that is possible to switch together at once between two possible states, open and closed. Such states must look different to make the plantxel suitable for creating two-color displays, which represents the least required condition for a display to show information. Using techniques such as dithering would also allow to obtain a higher range of perceived colors. The size of a plantxel depends on the number of leaves that is possible, or desired, to control, which in turn depends on the plants used, on the control system, and on the display purposes.

A dynamic display made of controllable plantxels suitably arranged in the desired shape may allow for a plethora of useful applications. For instance, display providers can sell their space in time slots, making sort of dynamic mini-crop circles. Moreover, the plant-based nature of such solutions would allow converting static flowerbeds or shrubs into dynamic and controllable displays, in fact increasing the available space for advertisement. Plantxels may also represent the building block for engaging dynamic art installations in public spaces.

Many thigmonastic plants can be potentially used as basis for building plantxels (e.g. *Biophytum sensitivum*, *Dionaea muscipula*, *Oxalis rubra*, *Mimosa pudica*, etc.). Choosing a plant implies choosing the possible control systems and, among them, the most suitable one for the intended deployment and desired performances.

In this paper, we will focus on a plantxel made of leaves of *Mimosa spegazzinii*, that is a variant of *Mimosa pudica*. Both plants react similarly to the same external stimuli (such as electrical, vibration or touch), have similar structure and similar shape of leaves, with the difference that *Mimosa spegazzinii* is more resistant against colder temperature, and it usually tends to grow in form of a shrub.

FEASIBILITY STUDY

The basic concept behind a controllable plant-based display is that each plantxel should be able to represent at least a binary information. Since a plantxel should switch between two different states (extremes of open and closed leaves), such states must be distinguishable by the human eye. In order to understand if a plantxel based on *Mimosa spegazzinii* can provide such a behavior, we conducted a feasibility study.

In particular, we focused our attention on the perceived color difference between the two states of the plant. The main goal of this study was to investigate the levels of contrast ratio that are possible to achieve by a single plantxel. Also, we wanted to understand if such contrast ratio depends on the leaves density, information that will be helpful to designers and practitioners to prepare plants for building plantxels.

Contrast Ratio and Leaves Density

Before describing the procedure of the study, here we briefly introduce and describe contrast ratio and leaves density that represent reference measures in the study.

Contrast Ratio

One of the most important properties of a display system is the contrast ratio, defined as the ratio of the luminance of the brightest color (usually white) compared to the darkest color (usually black) that the system is capable of producing [4]. While such definition seems quite self explanatory, to our knowledge there is no official, standardized way to measure contrast ratio that is applicable across different display hardware. This makes the measurement of the contrast ratio quite difficult and not easily comparable with other systems, especially when considering non-conventional display hardware.

However, there has been a standardization process conducted for VRT terminals [8, 12] that can be a starting reference for our evaluation study. Also, the World Wide Web Consortium (W3C) defined a document containing a set of Web Content Accessibility Guidelines (WCAG) [5] that can be applied in our approach. The W3C consortium introduced the need for a minimum contrast between text color and background color, in order to provide accessible information by setting a minimum level of readability. To this end, the WCAG include the following definition of contrast ratio (C_r) between the text and background colors:

$$C_r = \frac{L_1 + 0.05}{L_2 + 0.05} \tag{1}$$

where L_1 is the relative luminance of the lighter color, L_2 is the relative luminance of the darker color, and $1 \geq L_1 \geq L_2 \geq 0$. The definition of relative luminance L corresponds to the Y component of the color in the CIE 1931 XYZ color space [22].

According to the above definition, $C_r \geq 1$ for any couple of colors. In particular, $C_r = 1$ if the colors are the same, while $C_r = 21$ is the highest possible value (e.g. for black and white). The W3C suggests a minimum contrast ratio $C_r = 3$ for large text. However, since such values are derived from calculations for body text (based on [8, 12]), larger text can result accessible also if $C_r \leq 3$. Moreover, WCAG do not require a minimum contrast ratio for text that is part of a logo or brand name, which is often the case of large texts in advertisements. These considerations means that $C_r = 3$ can be considered a good value, but lower values can still be acceptable.

In the following, we consider the contrast ratio as defined by Equation 1 for evaluating the contrast ratio of a plantxel. We also compared the resulting contrast ratio with the threshold value defined by the W3C in the WCAG.

Leaves Density

Considering an image (e.g. a photograph) of the top view of a plant, we define the leaves density as the ratio between the number of pixels representing the leaves, and the total number of pixels of the image. This means that an image where there are only leaves has a leaves density $d = 1$, while an image with no leaves has a leaves density $d = 0$.

Since we are interested in two states of each plant (i.e. with open and closed leaves), we considered 3 different values based on the above definition of leaves density:

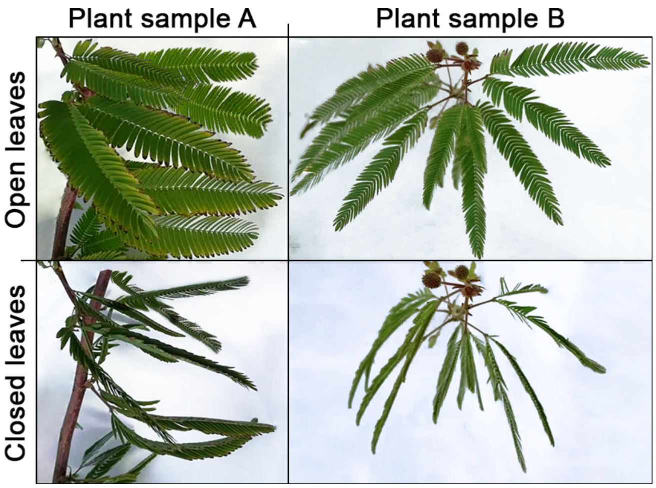

Figure 2. Two sample plants used for our feasibility evaluation, with different contrast ratios and leaves density (left: $C_r = 2.31$**,** $d_O = 0.70$**,** $d_C = 0.31$**,** $\Delta_d = 0.39$**; right:** $C_r = 1.31$**,** $d_O = 0.29$**,** $d_C = 0.13$**,** $\Delta_d = 0.16$**).**

- open leaves density (d_O), representing the leaves density measured when the plant has all the leaves open;
- closed leaves density (d_C), representing the leaves density measured when the plant has all the leaves closed;
- difference between the above densities (Δ_d).

Procedure

We considered 12 sample specimens of *Mimosa spegazzinii*, with leaves covering (while open) rectangular areas, ranging from 8 cm^2 to 20 cm^2. Among these 12 specimens, 3 were made by a single leaf. Each plant had a white paper sheet at the basis, i.e. under the leaves. The rationale behind this choice is to make the plantxel appearing white when the leaves are closed, and dark green when the leaves are open.

Since we wanted to evaluate the perceived contrast ratio while looking at the display from a certain distance, we photographed each plant from the top (see Figure 2) in two different conditions: with all the leaves open, and with all the leaves closed. All the photographs have been made with the same lighting conditions.

Each picture is then cropped to the minimum bounding rectangle that contains the leaves (when they are completely open). Then, we computed a mean color for each image by computing the average color among all the pixels in each image. The colors obtained from the two images of the same plants are used for computing the contrast ratio C_r of each plant. For each plant, we also evaluated the aforementioned values of leaves density d_O, d_C and Δ_d.

Results and Discussion

Contrast Ratio Evaluation

We were interested to estimate the maximum contrast ratio that can be provided by a single plantxel. Our tests showed a maximum contrast ratio of 3.55, which corresponds to a single-leaf specimen. Since one plant is usually made by more than one leaf, we consider this as a sort of upper limit for the contrast ratio. By excluding the single-leaf specimens from our considerations, the maximum contrast ratio was 2.39, which is lower than the minimum value suggested by the WCAG for large texts ($C_r = 3$). However, since we considered photographs of non-customized plants, it is plausible that higher contrast ratios can be achieved with the help of experts in gardening.

We also tried to evaluate the contrast ratio of a synthetic image couple, made by replicating the same leaf (both in the open and closed version). While this has been made using Photoshop, the synthetic image is somehow comparable with a photograph of a plant adjusted and customized by an expert. In this case, the contrast ratio was of about 2.80.

It is worth noting that, to our knowledge, the only comparable solution to our plantxel is MOSS-xels [14]. However, in their paper authors did not provide any evaluation based on contrast ratio or analogous measurements, aimed at understanding if their solution is able to provide two pixel colors that are distinguishable by the human eye. Based on the images provided in [14], we were able to compute the contrast ratio of MOSS-xels, which resulted lower than 1.10 (and consequently lower than our values of 3.55, 2.80 and 2.39). This value does not allow for displaying texts that are easily readable by the human eye.

It should be noticed that our evaluation has only considered top views of each specimen, although plants are not flat and their appearance depends also on the viewing angle. However, a typical installation of a plant-based display should better be observed perpendicularly to the display plane and from a distance, as indeed for common big displays. Thus focusing our evaluation on top views seems a reasonable assumption.

In order to give a sense of how a plantxel-based display should appear with contrast ratios similar to the obtained values, i.e. higher than 2 but lower than 3, we have also developed a simple web application that converts black and white images to a simulated plant-based display[1]. Each white pixel is converted in a randomly chosen picture among the available images of closed plantxels, while black pixels are converted in a randomly chosen picture among the available images of open plantxels. Using three possible plantxels with $2 \leq C_r \leq 2.4$, a sample of a resulting image is shown in Figure 1.

Contrast Ratio vs. Leaves Density

We were also interested in understanding which feature of the plant might affect the contrast ratio of the plantxel. Since the contrast ratio depends on the two considered states of the leaves (i.e. open and closed), and taking into account the definition of leaves density, we decided to investigate a possible relation between contrast ratio and leaves density.

In particular, we observed that increasing the number of leaves in a plantxel would result in a higher area covered by open leaves (and thus a higher d_O), but also in a higher area covered by closed leaves (and thus a higher d_C). This means that increasing the number of leaves does not necessarily imply increasing the C_r, due to the residual area covered by closed leaves, that in fact reduces the visibility of the white background. Intuitively, this also means that the best plantxel in terms of C_r is composed of the minimum possible number of

[1] Such application is available at: https://usi.unipa.it/plantxel/

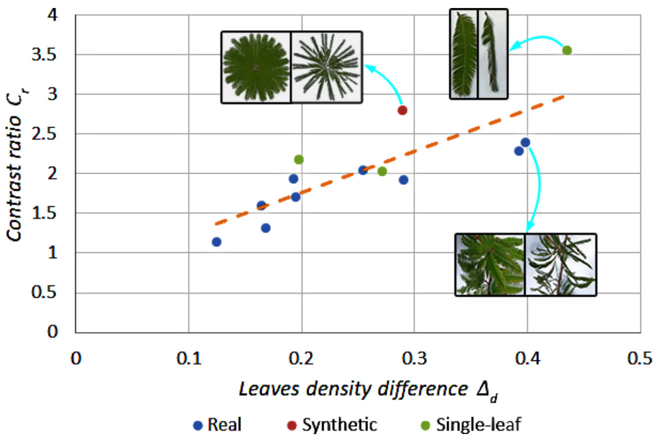

Figure 3. Scatter plot and linear regression of contrast ratio vs. leaves density difference, along with one couple of images (open/closed leaves) for each type of plant used for our tests (real, synthetic and single-leaf).

leaves that allows achieving the higher d_O. This would maximize d_O and, at the same time, minimize d_C. More generally, the objective is thus to maximize the Δ_d value.

Having this in mind, we compared the different values of contrast ratio with Δ_d. Figure 3 shows a scatter plot with linear regression, showing that contrast ratio tends to increase with Δ_d, which is in line with our intuition. This represents a relation between the physical arrangement of leaves and the maximum achievable contrast ratio. This is also of great interest to designers of plantxels, since higher contrast ratios can be achieved by increasing Δ_d. In conclusion, finding a good trade off between number of leaves and contrast ratio is thus the key for building effective plantxels.

PROTOTYPE

In this section, we describe the design choices and present a prototypical implementation of a plantxel control system using a *Mimosa spegazzinii* plant and air stimuli. Our goal is to provide a practical overview of the prototype, describe initial experience with the prototype plantxel, and outline possible limitations that can inform future design of plantxels and plant-based displays.

Design Choices

Our design aims at a scalable and effective solution, taking into account the type of stimuli, maintenance and wellness of the plants, and hardware needed for the implementation in different real-world settings.

Type of Stimuli and Scalability

As mentioned before, *Mimosa spegazzinii* can be stimulated to close its leaves by different external inputs, such as electrical stimulation that requires attaching a number of electrodes to the stem of the plant [21]. In this case, the number of electrodes and the needed current for stimulation depend on the plant size, thus making this solution less scalable. Furthermore, this would necessarily constrain to control a whole plant and not a single part of it, which can theoretically be possible in some context. Finally, electrical input is not plant-friendly, and exposes the plant to dangers (e.g. power surges should carefully be managed to avoid unexpected damages).

For our prototype, we decided to use air stimuli to trigger the closure of leaves. In particular, we opted to use short bursts of high-speed air flows. This is definitely the most "natural" stimulus for the plants, being similar to wind gusts they experience in the wild, and thus less stressing. Furthermore, it is less invasive and easily scalable to plantxels of different sizes, and can be adapted to control either a single leaf or different leaves, even from different plants. The specific needed hardware is quite simple to use, deploy and maintain, being composed mainly of pipes and joints.

Base of Plantxel

To achieve the best result in terms of contrast ratio, we decided to use a layer of white gravel to cover the terrain surface below the plants. Since during our feasibility study we observed that, on average, the luminance of leaves is lower than 0.5, the choice of a white background color allows for maximizing the contrast ratio provided by the plantxel (according to Equation 1). Moreover, gravel also prevents water evaporation, thus keeping the topsoil at a good moisture level for a longer time, with no need of frequent watering. Finally, this choice also results in a pleasant aesthetics of such an installation and construction of larger plant-based displays.

Control System

We decided to implement a controllable system that can direct air flows to the plant from a common air source, such as a fan or pressurized air container. The air streams are then controlled by solenoid valves placed between the air source and the plant, which in turn are driven by computer-controlled relays. This allows using one single air reservoir as "energy source", which can be suitably placed in a safe, hidden, and even remote place, and then distributed to the plants through pipes. Controlling a new plantxel would simply require a solenoid valve and pipes to direct the air flow to the plant.

Implementation Details

We implemented a working prototype of a single plantxel that can be used in a small-scale deployment of plant-based display in a real-world setting. The prototype is shown in Figure 4. It consists of a Raspberry Pi 3 Model B board, relay board with eight channels, solenoid valve, air source, and air pipes. The central Raspberry Pi board runs the control logic and operates the relay board, in our case only one relay. The relay is connected to the solenoid valve that when opened directs the air flow through the pipes from the air source, i.e. a pressurized air can, to the plant.

Experience with the Prototype System

We were interested in understanding the performance of the plantxel regarding closing the leaves (responding to stimulus) and staying in the closed state (keeping the information). We conducted several tests to measure closing and opening times of the plantxel. Our tests were conducted at an operating temperature of about 20°C, which represents an optimal condition for the plant [24].

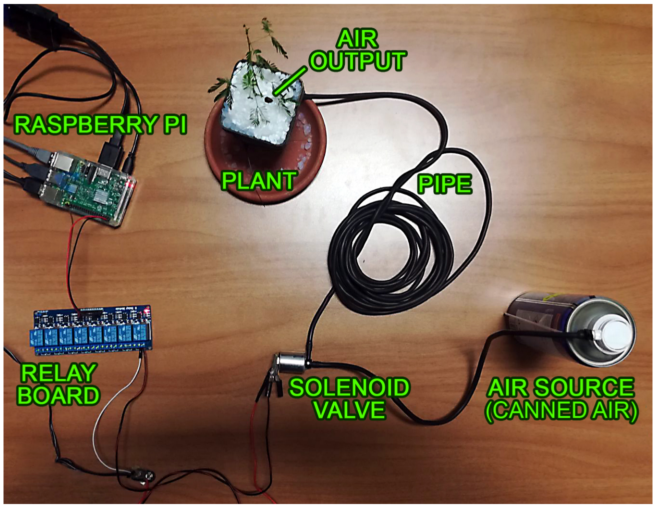

Figure 4. Overview of the implemented plantxel.

We controlled the valve to let the air pass to the plant for one second, then we observed the closing and re-opening time. We repeated the tests at least 15 minutes after the leaves were fully open again. We let the air pass again through the valve and observed the values. We repeated this procedure three times.

Considering our plant specimen, we observed a quick closing of the leaves (from 4 to 6 seconds approximately). With such a stimulus, we can keep the plantxel in the closed status for approximately 18 minutes. According to [24], the time needed for reopening the leaves is actually not always the same: it depends on the specific specimen, as well as on many other external factors that make the quantitative analysis hard to perform. For instance, ambient temperature and nature of the stimulus usually affect the re-opening time. On the other end, it is worth noting that our prototype system provides opening and closing timings that are faster compared to the previous plant-based displays, e.g., MOSS-xels that needs 5 to 60 minutes to transit between the two states [14]. Also, it is worth noting that the prototype worked correctly in all the tests we performed and was effective in stimulating the plant and closing its leaves.

Limitations

There are certain limitations of both the conceptual idea as well as of the plantxel prototype. First, we have neither included nor discussed any mechanism for allowing plants watering in an actual deployment with multiple plantxels. We do not expect big issues since it is possible to use a drip irrigation system that does not interfere with both the control system and the plants thigmonastic behavior.

For a long-term deployment, there could be other factors that can affect the feasibility of a big plant-based display. Plants require constant maintenance for staying in good shape and health, both in terms of watering and leaves pruning, which could influence the shape and position of the plant and its leaves. Also, temperature should be relatively constant and in a range between 20 and 35°C, which is the optimal temperature to provide good thigmonastic responses of the plant [24]. This would limit the deployments to indoor spaces or, in case of outdoor installations, to countries with compliant climate.

Finally, previous work in the field of botanical physiology showed that *Mimosa spegazzinii* tends to “remember” previous stimuli and stops responding to them [9]. To avoid this behavior, there should be a limited exposure time and number of stimuli per day per plant. A long-term study would help to better understand such behavior.

CONCLUSION AND FUTURE WORK

In this work we introduced the plantxel, that is a pixel made of plants, which can be used as the main building block to compose plant-based displays (Figure 1). We thus presented the basics of our conceptual idea, along with some possible applications. As a first step towards the realization of a plantxel, we investigated whether the difference between two states of a plant (i.e. open and closed leaves) is able to convey a binary information, being thus distinguishable from the human eye. To this end, we conducted a feasibility study aimed at estimating the contrast ratio provided by a plantxel. We found a maximum contrast ratio value of 3.55 for single-leaf plantxels, and a slightly lower contrast ratio of 2.39 for more realistic plantxels made of several leaves. We discussed how such lower contrast ratios can still be suitable for certain display applications, and how changing the leaves density can influence the contrast ratio of a plantxel.

We then built a plantxel prototype using a *Mimosa spegazzinii* plant and air stimuli to test the practical feasibility of our concept. We implemented the control system using a Raspberry Pi that drives a solenoid valve to control the air flow, which in turn is used as a stimulus for the plant to close its leaves. Our preliminary lab tests showed the effectiveness of such approach in closing the leaves (response to stimulus ranging from 4 to 6 seconds) and maintaining the closed state for approximately 18 minutes.

As a possible development, in addition to *Mimosa spegazzinii*, we would consider using other thigmonastic plants that could lead to better plantxels. For instance, leaves of *Mimosa pudica* are generally more parallel to the ground when compared with *Mimosa spegazzinii*, making it easier to achieve higher contrast ratios. Furthermore, the leaves color of *Oxalis rubra* and *Dionaea muscipula* differs from green and can be combined to create multicolor plant-based displays. It would be also interesting to investigate the energy consumption of plantxel-based displays, since during our tests it appeared to be very low. In fact, we envision the possibility to power our system with solar panels or other sources of green energy. Finally, a further step would be to build an actual plant-based display with multiple plantxels and evaluate it in a real-world deployment through a long-term study. This would allow to conduct user testing, and to estimate other typical parameters of the display, such as plantxel refresh rate and viewing angle limits.

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REFERENCES

1. Robert D. Allen. 1969. Mechanism of the Seismonastic Reaction in Mimosa pudica. *Plant Physiology* 44, 8 (1969), 1101–1107. DOI: http://dx.doi.org/10.1104/pp.44.8.1101
2. Gilbert Beyer, Florian Alt, Jörg Müller, Albrecht Schmidt, Karsten Isakovic, Stefan Klose, Manuel Schiewe, and Ivo Haulsen. 2011. Audience Behavior Around Large Interactive Cylindrical Screens. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. ACM, New York, NY, USA, 1021–1030. DOI: http://dx.doi.org/10.1145/1978942.1979095
3. Elio Capellari. 1970. Remote-controlled display device for selectively displaying signs or words. (1970). US Patent 3,501,761.
4. Hsi-Hao Chung and Sun Lu. 2003. Contrast-ratio analysis of sunlight-readable color LCDs for outdoor applications. *Journal of the Society for Information Display* 11, 1 (2003), 237–242. DOI: http://dx.doi.org/10.1889/1.1831713
5. World Wide Web Consortium. 2008. Web Content Accessibility Guidelines (WCAG) 2.0. https://www.w3.org/TR/WCAG20/. (2008). Accessed: 24 Jan 2018.
6. Nigel Davies, Sarah Clinch, and Florian Alt. 2014. *Pervasive Displays: Understanding the Future of Digital Signage*. Morgan and Claypool.
7. Thiago Paes de Barros De Luccia and Pedro Friedman. 2011. Boolean function applied to Mimosa pudica movements. *Plant Signaling & Behavior* 6, 9 (2011), 1361–1364. DOI: http://dx.doi.org/10.4161/psb.6.9.16445
8. International Organization for Standardization. 1992. Ergonomic requirements for office work with visual display terminals (VDTs) - Part 3: Visual display requirements. (1992). ISO 9241-3, Amendment 1.
9. Monica Gagliano, Michael Renton, Martial Depczynski, and Stefano Mancuso. 2014. Experience teaches plants to learn faster and forget slower in environments where it matters. *Oecologia* 175, 1 (01 May 2014), 63–72. DOI: http://dx.doi.org/10.1007/s00442-013-2873-7
10. Andrew Glassner. 2004. Crop art. Part 1. Computer graphics. *IEEE Computer Graphics and Applications* 24, 5 (Sept 2004), 86–99. DOI: http://dx.doi.org/10.1109/MCG.2004.25
11. John Hardy and Jason Alexander. 2012. Toolkit Support for Interactive Projected Displays. In *Proceedings of the 11th International Conference on Mobile and Ubiquitous Multimedia (MUM '12)*. ACM, New York, NY, USA, Article 42, 10 pages. DOI: http://dx.doi.org/10.1145/2406367.2406419
12. American National Standards Institute. 1988. American National Standard for Human Factors Engineering of Visual Display Terminal Workstations - Section 6. (1988). ANSI-HFES-100.
13. Ayumi Kawakami, Koji Tsukada, Keisuke Kambara, and Itiro Siio. 2011. PotPet: Pet-like Flowerpot Robot. In *Proceedings of the Fifth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '11)*. ACM, New York, NY, USA, 263–264. DOI: http://dx.doi.org/10.1145/1935701.1935755
14. Takaki Kimura and Yasuaki Kakehi. 2014. MOSS-xels: Slow Changing Pixels Using the Shape of Racomitrium Canescens. In *ACM SIGGRAPH 2014 Posters (SIGGRAPH '14)*. ACM, New York, NY, USA, Article 20, 1 pages. DOI: http://dx.doi.org/10.1145/2614217.2630572
15. Satoshi Kuribayashi, Yusuke Sakamoto, and Hiroya Tanaka. 2007. I/O Plant: A Tool Kit for Designing Augmented Human-plant Interactions. In *CHI '07 Extended Abstracts on Human Factors in Computing Systems (CHI EA '07)*. ACM, New York, NY, USA, 2537–2542. DOI: http://dx.doi.org/10.1145/1240866.1241037
16. Satoshi Kuribayashi and Akira Wakita. 2006. PlantDisplay: Turning Houseplants into Ambient Display. In *Proceedings of the 2006 ACM SIGCHI International Conference on Advances in Computer Entertainment Technology (ACE '06)*. ACM, New York, NY, USA, Article 40. DOI: http://dx.doi.org/10.1145/1178823.1178871
17. Wataru Kurihara, Akito Nakano, and Hisakazu Hada. 2017. Botanical Puppet: Computer Controlled Shameplant. In *2017 Nicograph International (NicoInt)*. 68–71. DOI: http://dx.doi.org/10.1109/NICOInt.2017.16
18. Carl Linnaeus. 1751. *Philosophia Botanica*.
19. Mozilla. 2013. Milestone: Firefox crop circle created in an oat field. https://blog.mozilla.org/community/2013/06/24/milestone-firefox-crop-circle-created-in-an-oat-field/. (2013). Accessed: 25 Jan 2018.
20. Ken Nakagaki, Luke Vink, Jared Counts, Daniel Windham, Daniel Leithinger, Sean Follmer, and Hiroshi Ishii. 2016. Materiable: Rendering Dynamic Material Properties in Response to Direct Physical Touch with Shape Changing Interfaces. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 2764–2772. DOI: http://dx.doi.org/10.1145/2858036.2858104
21. Ivan Poupyrev, Philipp Schoessler, Jonas Loh, and Munehiko Sato. 2012. Botanicus Interacticus: Interactive Plants Technology. In *ACM SIGGRAPH 2012 Emerging Technologies (SIGGRAPH '12)*. ACM, New York, NY, USA, Article 4, 1 pages. DOI: http://dx.doi.org/10.1145/2343456.2343460

22. Thomas Smith and John Guild. 1931. The C.I.E. colorimetric standards and their use. *Transactions of the Optical Society* 33, 3 (1931), 73. http://stacks.iop.org/1475-4878/33/i=3/a=301

23. R. Snow. 1925. Conduction of excitation in the leaf of mimosa spegazzinii. *Proceedings of the Royal Society of London B: Biological Sciences* 98, 688 (1925), 188–201. DOI:http://dx.doi.org/10.1098/rspb.1925.0030

24. Walter Stiles. 1994. *Principles of plant physiology*. Discovery Publishing House.

25. Alexander G. Volkov, Justin C. Foster, Talitha A. Ashby, Ronald K. Walker, Jon A. Johnson, and Vladislav S. Markin. 2010. Mimosa pudica: Electrical and mechanical stimulation of plant movements. *Plant, Cell & Environment* 33, 2 (2010), 163–173. DOI: http://dx.doi.org/10.1111/j.1365-3040.2009.02066.x

26. Julie R. Williamson, Euan Freeman, and Stephen Brewster. 2017a. Levitate: Interaction with Floating Particle Displays. In *Proceedings of the 6th ACM International Symposium on Pervasive Displays (PerDis '17)*. ACM, New York, NY, USA, Article 24, 2 pages. DOI:http://dx.doi.org/10.1145/3078810.3084347

27. Julie R. Williamson, John Williamson, and Daniel Sundén. 2017b. Sunken Ripples: Exploring Performative Interactions with Non-planar Displays. In *Proceedings of the 6th ACM International Symposium on Pervasive Displays (PerDis '17)*. ACM, New York, NY, USA, Article 12, 6 pages. DOI: http://dx.doi.org/10.1145/3078810.3078824