Attempt on Plant Machine Interface

Towards Self-monitoring Plant Systems

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Abstract— **In this paper, we investigate possible means of communication between plants and machines. Plants are capable of sensing various environmental information. In particular, Avocado trees have an apparent response to increasing draught level. We read out two different communication channels: morphological changes (leaf inclination) and electric potential of the stem (biopotential) by using distance sensors and biopotential electrodes, respectively. Our experimental results show that leaf inclination is a reliable candidate to automatically trigger on irrigation, whereas the biopotential can be used to automatically stop the irrigation. Hence, through systematic experiments we demontrate that morphological changes and biopotentials provide suitable control signals for interfacing plants with machines, and open a possibility to exploit abilities of plants in robotic systems.**

I. INTRODUCTION

Plants in terms of biomass are the dominant living organisms on earth. They evolved and became adapted to various environments through time. Plants exploit patches which are rich in resources and exhibit light gradient growth [1], [2] by changing their morphology (root/stem length, leaf growth pattern) or the dynamics of internal states (e.g. number of chloroplasts on the leaf surface). The ability to sense and compute these environmental influences and to produce a goal-oriented response is regarded as a desired ability of machines. In the cybernetics sense defined by Norbert Wiener [3], it is appropriate to extend the science of communication and control to plants and machines, given the advancement of interfacing techniques. This is especially important for developing technologies which utilize the intrinsic computational capabilities of a pervasive species like plants. These technolgies can help to support and sustain vegetative life under harsh conditions. On the other hand plant's signals could be useful as robust sensors to translate complex information from the environment, considering plants as competitive computational entities. Furthermore, both approaches can be merged to optimize resource allocation for plants under artificial plant growth conditions.

Lately, a few groups have tackled the problem to connect plants with devices. An approach managed to provide a more accessible interaction between plants and humans by transforming plant signals into visual and acoustic feedback can be found in [4], [5]. This technically enhanced anthropomorphism enabled people to develop an emotional bond with their pet plants more easily.

The observation of various parameters concerning the growth of crop plants (phytomonitoring) on a large scale is of big interest to agriculture. Automated visual detection system of leaf inclination was developed by [6], though the difficulty in detecting large number of plants resides. Ton et al. developed a commercial system (Phytech Ltd.) for growers [7]. The benefits of this system were shown by Gurovich et al. who was able to increase the yield in an avocado orchard [8]. They also evaluated electric signal (biopotential) measurements to gain a deeper insight into the processes that take place in every plant. Biopotentials occur between the in and outside of a living cell due to divergent ionic concentrations. The metabolic activity and therefore also the bioelectric parameters are affected by the multiple dynamic equilibria that form the interior milieu in a living organism. It is in turn influenced by the incorporation of a variety of environmental influences, such as water stress, light yield and the availability of nutrients. The change of the biopotential of avocados and other fruit trees in response to different stresses were studied in [9]. They further found significant biopotential reactions to drought in two-year old avocados [10] [11]. Fromm et al. observed a daily rhythm of biopotential in maize plants, reaction to drought and a correlation of the second with a change in the gas exchange [12]. In a review he gave a broad overview over the field of examining electromagnetic plant signals [13]. A unique approach can be found in [14], where Correll et al. constructed a garden with plants, that are cultivated by robots. The robots automatically irrigate the plants and harvest mature fruits.

The Plantae kingdom was so far almost completely disregarded as suitable counterparts in cybernetic systems despite the fact that especially higher plants have proven to display a wide range of different behaviours and information collecting competence. Furthermore the communication protocol that enables a machine to elaborately understand the plant signal has yet to be established.

One of the basic resources a plant relies on is water. The fundamental functions of the plant such as photosynthesis and the upkeep of its morphological state are heavily dependent on the availability of water. Cell turgor, a hydrostatic pressure inside the vacuole of a plant cell, keeps plants erect and grants rigidity. Stress due to ongoing drought

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results in typical visual signs of water shortage and wilting. Furthermore it affects the ability to transport nutrients inside the vascular tissue and consequently immediately confines the metabolic rate. These signs can be evaluated among other methods either visually or electrophysiologically, that is, assessing the leaf positions or by recording the electrical potential (biopotential) within the trunk of the plant, respectively. These measurements can in turn be used for the device counterpart to respond adequately and provide the plant with water when needed. This study attempts the first steps towards a closer conjunction between plants and machines. We focus on the morphological and biopotential change of Avocado tree and manage communication between the plant and a machine by conveying information from the plant to a machine and back again in order to form a close-loop interaction. In section II we enumerate the materials and methods, in section III we present our experiments and results and close with some concluding remarks in section IV.

II. MATERIAL & METHODS

In this section we present the plant stimuli, the control algorithm, the actuation system and analysis method used for interfacing plants with robotic devices.

A. Leaf Inclination

The leaf inclination is an indicator of draught level. Ensuring the portability of plant device in future use, we built a disc by rapid prototyping to support 6 infrared (IR) distance sensors (Sharp GP2D120 83) arranged in a hexagonal shape (Fig. 1 B). The disc was attached to the stem of the plant in 4 to $30\,cm$ distance to the canopy which is also the range of the distance sensors. They cover $360°$ granting redundancy and allowing to reliably read the morphological state of the avocado. The measured values from the sensors were recorded and processed on a controller board (*ATmega1280 microprocessor Arduino board*). This implementation thus remains valid if the plant grows in height.

B. Biopotential

To assess the electrical state of the avocado we utilised biopotential electrodes. Measuring a biopotential – a mV order weak electric potential that is thought to be measured in a plant [15] – is still a challenging attempt for engineers to interface plants to machines. First, biopotentials show a low ratio of signal to noise, being affected by environmental noises. To overcome this issue, a standard instrumentation amplifier consisting of three op-amps and a potentiometer to adjust the gain was used to increase this signal. Because biopotentials differ from plant to plant, the gains are adjusted to the range of 0 to $5\,V$. Furthermore, every 10 seconds 1000 values from the sensors were sampled at 10 kHz and averaged to minimize high-frequency noise. The controller board and the amplifier were placed in a cardboard box which was lined with aluminium foil and subsequently grounded. Second, the electrodes damage the tissue where they are inserted in the stem thereby degenerating the conditions at the measuring point. To alleviate the second problem, we produced Ag/Ag-Cl electrodes by electrolyzing a silver wire ($\phi\,0.4\,mm$) in dissolved KCl for about $30\,s$, to be able to maintain a prolonged redox reaction with the circumfluent electrolyte. Electrodes were inserted directly into the stem, one placed a few centimetres above the soil while the other just below the canopy (Fig. 1). For reference, a ground electrode was put into the soil at the outer edge of the pot just below the surface. The electrode positions were initially adjusted such that competent level of biopotentials could be measured.

C. State Evaluation for Automatic Irrigation

In our experiments, we employ the leaf inclination to start the irrigation, and the biopotential to stop it. We therefore developed an algorithm to automatically irrigate the plant depending on these two variables.

Let $\boldsymbol{y}_n$ be the series of data of one of the distance sensors ($\boldsymbol{y} = [y_0...y_{n-1}]$, $n \in \mathbb{Z}|0 \ldots n-1$) at time step n. We define $T = 1\,cm$, a threshold which is able to maintain the plant healthy within a reasonable range. At time n, the following conditions are checked:

$$|\boldsymbol{y}_n - \boldsymbol{y}_t| > T \tag{1}$$

where t is the reference point for the two thresholds. The upper and lower threshold values, $\boldsymbol{y}_t + T$ and $\boldsymbol{y}_t - T$ are defined at the beginning of the experiment by initializing $\boldsymbol{y}_n = \boldsymbol{y}_t = \boldsymbol{y}_0$. If the leaves rise above $\boldsymbol{y}_t + T$ or fall below $\boldsymbol{y}_t - T$ then the reference point of the threshold is being renewed ($\boldsymbol{y}_t = \boldsymbol{y}_n$) and the two thresholds are recalculated accordingly. Furthermore if the lower threshold is crossed then the water supply is switched on and the irrigation starts. Recalibrating the thresholds grants validity to the algorithm even if the plant grows in height.

To stop the irrigation, the changes in plant's biopotential are considered. Our experimental observations pointed at an increase of the biopotential after the avocado receives water. We use this criterion to stop the irrigation. If $\boldsymbol{z}$ ($\boldsymbol{z} = [z_0...z_{n-1}]$, $n \in \mathbb{Z}|0 \ldots n-1$) is the biopotential then the relation which determines whether the water flow should be interrupted is:

$$\boldsymbol{z}_n > \boldsymbol{z}_i * p \tag{2}$$

where n is the actual time step, i is the time at the beginning of the irrigation event and $p = 1.15$ chosen according to prior experimental observations. Fig. 1 C schematically shows how both algorithms are used to trigger the irrigation on and off during a close-loop experiment.

D. Water Supplier

Constant and slowly dripping irrigation was provided by a flow regulator for gravity infusions (*B.Braun Exadrop*). This allowed the automatic regulation of the flow up to $250\,ml$ per hour from the water tank. The hydrostatic pressure of the water tank was maintained for every experiment. The lower end of the tube was buried in the soil near the stem.

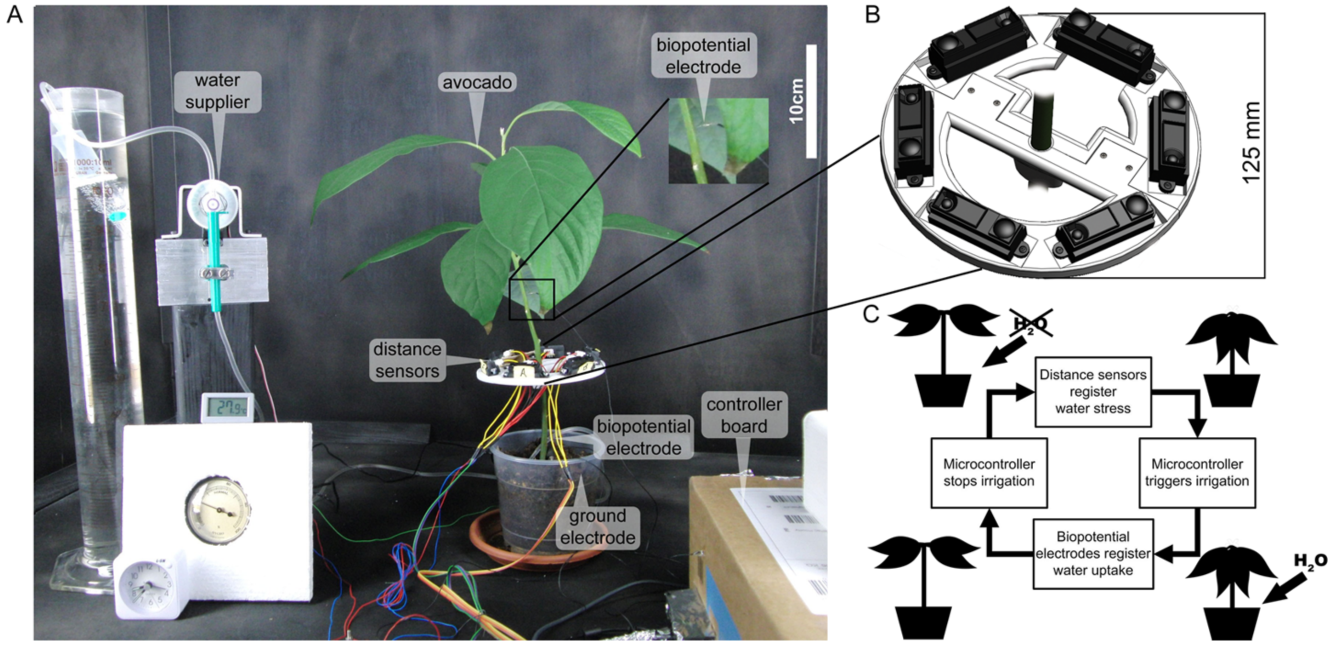

Fig. 1: (A) Snapshot of the whole experimental setup. (B) The disc that supports the six distance sensors which compose the leaf inclination detection system. (C) Schematic of the closed-loop interaction to which the experiments should lead.

The Exadrop valve was controlled by a servo motor (*Futaba S3003*), operated by the same controller board.

E. Growth and Experimental Environment

The Avocado tree (Persea americana) has several advantages for the usage in indoor experiments. It has a rigid stem, shows reasonable growth speed, and the seeds are commercially available almost everywhere. It has lance-shaped leaves with a large surface which is suitable for detection with infrared sensors and it can grow at room temperature and under typical office lighting conditions [16].

Avocados which we used for the experiments were grown in pots of about 1 litre capacity for roughly 6 months before the beginning of the experiments, and have reached an average height of about $40\,cm$. The experiments were carried out in a normal office room, whose climate was kept at $26°C$ and 35% humidity, being maintained the same lighting condition. A webcam took a picture of the whole setup every 10 minutes, in order to verify the validity of the distance sensors values.

The overall system setup is listed in Table I.

TABLE I: Components of the Experimental Setup

Device	Description / Type
Infrared distance sensor	Sharp GP2D120 83
Valve for water supplier	B.Braun Exadrop flow regulator
Servo motor	Futaba S3003
Biopotential electrodes	Ag/Ag-Cl (handmade)
Controller board	Arduino MEGA, ATmega1280
Lighting	(1) Steffen fluorescent lamp $8\,W$
	(2) Philips TL-D 90 De Luxe Pro $58\,W$/950
Plant	Avocado (Persea americana)

F. Time-Frequency Analysis

To assess the effect of irrigation on periodic life activity of plants along the time course, the continuous wavelet transformation with the Meyer mother wavelet $\psi(t)$ [17] was adapted to the measurements, $x(t)$, of a time series of either leaf inclination or biopotential around the irrigation event during epochs:

$$W_\psi(a,b) = \frac{1}{\sqrt{a}} \int_{\infty}^{-\infty} x(t)\psi^* \left(\frac{t-b}{a}\right) dt \tag{3}$$

where $W_\psi(a,b)$, a, and b indicate coefficient, scale (that was transformed into pseudo-frequency), and time shift of the wavelet transform, respectively. Subsequently, normalized wavelet power for each coefficient $w(a,b)$ was calculated:

$$w(a,b) = |W_\psi(a,b)|^2 / \sigma^2 \tag{4}$$

where σ is the standard deviation of each epoch. Here, epochs were defined as intervals from a half hour before to two hours after the irrigation event starts. These power values were averaged across all the leaves values for each experiment. By plotting the averaged set of $w(a,b)$, time-frequency analysis was obtained over the measurements.

III. EXPERIMENTS & RESULTS

In this section we describe manual (A,B) and semi-automatic (C) irrigation experiments as a study of control patterns in leaf inclination and biopotential signals. As a result of this study, an automatic closed-loop based on both leaf inclination and biopotential was achieved and described in D. Results of wavelet transform analysis is presented in E.

A. Manual Irrigation Effect on Leaf Inclination

In this experiment we evaluated the change in leaf inclination caused by manual irrigation. A baseline was recorded during two hours, then the plants were manually irrigated with about $50\,ml$ of water and the effect on the leaf inclination was observed for another four hours.

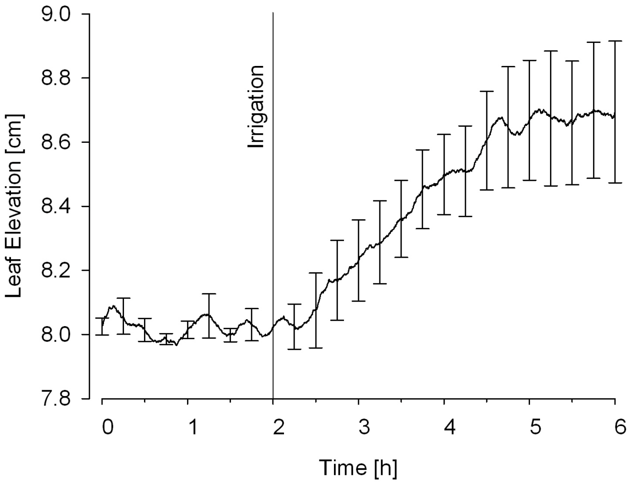

Fig. 2: The average normalised vertical movement of the canopy after an irrigation event with $50\,ml$ of water, measured with the sensor disc (n=8).

Fig. 2 shows the average vertical movement of the canopy of avocados. Because the initial height of the canopy differed from plant to plant, the values were normalised to the same level at the time of the irrigation event by multiplication with a fixed factor.

When the plant suffers from drought the leaves decrease very slowly. As soon as the irrigation event occurs a sharp rise of the canopy can be seen in the figure within 30 minutes. This indicates that the leaves almost reach their regular height two hours after the irrigation event. Differences between the plants may occur due to the different morphologies and different stages of water draught level.

Individual measured data sometimes showed sudden drops or jumps. This might be caused by the switch of detected leaves as they move up or down. We counteracted this effect by selectively rejecting sensors that produced a variance higher than 0.7. This precaution usually dismissed one to three sensors out of an array of six. The redundancy of the sensors enables the assessment of leaf changes with sufficient precision.

B. Manual Irrigation Effect on Biopotential

This experiment evaluates the effect of water addition on the biopotential of an avocado plant. Plants which showed mild signs of water draught level were initially equipped with electrodes. After 30 minutes of recording a baseline, about $50\,ml$ of water were added manually. Then the change of the biopotential was recorded for the next 5 and a half hours.

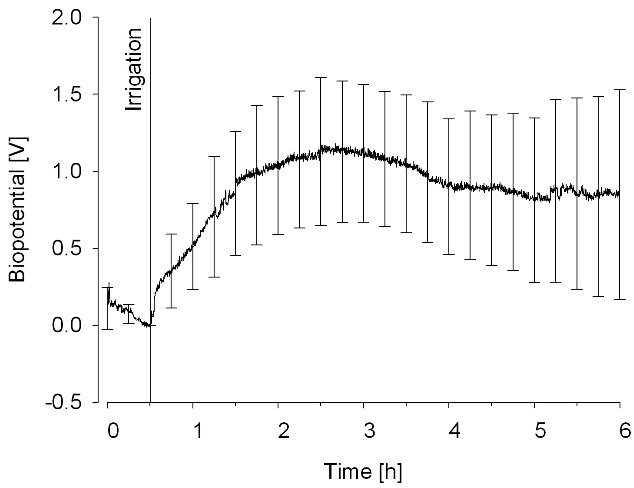

Fig. 3: The average normalised change of the biopotential after a manual irrigation event with $50\,ml$ of water (n=12).

Because the absolute biopotential differed greatly from plant to plant the measurements of all plants were normalised to the same level at the point of the irrigation event. In general the biopotential tends to drop more or less slowly as soon as the recording begins. If the biopotential does diverge from its initial trend, it does so by a sudden increase shortly after the irrigation event. The individual differences in the change of the biopotential are bigger than we expected. We recorded data from eighteen different avocado plants, six of which had to be rejected because the biopoential signal was lost during the recording. The height of the biopotential in the twelve remaining plants two hours after the irrigation event on average increased by $134 \pm 51\%$ relative to the original value just before the irrigation event.

These results plotted in Fig. 3 led us to the assumption that the water uptake could be characterised in general by a relative increase of the biopotential compared to the value just before the irrigation event. It has to be considered that the insertion of the electrodes may inflict significant damages to the tissue at the location of the electrode and may therefore influence the natural changes of the biopotential. Furthermore it can be also possible that various types of tissue within the stem transmit the biopotential differently.

C. Automated Irrigation by Leaf Inclination

A first attempt towards automatic experiments for plant-controlled irrigation was conducted using distance sensor values to trigger on the water supply. The irrigation was stopped by an implemented time-related event.

The plot in Fig. 4 represents five independent experiments of autonomous irrigation by leaf inclination. We sampled leaf inclination every ten seconds and evaluated the irrigation condition according to relation 1. When the distance sensors detect signs of water draught level, the water supply is being turned on and irrigates the plant with about $50\,ml$ per hour. During most of the time prior to irrigation the inclination of the leaves stays stable. Only in the last 24 hours before the predicted irrigation event the decrease of the leaf inclination accelerates. As soon as the irrigation is being triggered, the leaves ascend rapidly and almost reach their initial state after two to four hours.

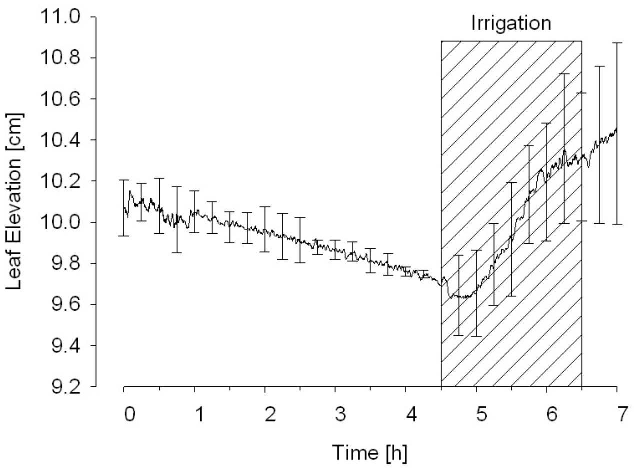

Fig. 4: The average normalized leaf inclination signal in autonomous irrigation (n=5).

This experiment demonstrates that the leaf inclination detection is able to assess signs of drought in the avocado plant and can be utilised as a control signal for irrigation.

D. Closed-Loop Interaction

The results in the experiments described in previous sections yielded that there exist patterns in the monitored signals which can be used to automatically close the loop in plant-machine interfaces and to autonomously control plant resources (e.g. water). These patterns were chosen to be: The decline of leaves to trigger on irrigation and the rise of the biopotential to stop the irrigation. We used both relation 1 and 2 to control the water resource consumption. After one algorithmic cycle the plant recovers and the process repeats. Fig. 5 shows a representative example of the controlled close loop interaction between an avocado plant and the robotic device.

E. Time-Frequency Analysis

Following the analysis described in section II-F, normalized wavelet powers for leaf inclination in manual and automatic irrigation experiments are shown in Fig. 6. For leaf inclination, an increase in power is observed in the range of $250 - 500$ μHz both in the manual and the automatic experiments, though the strength for the manual condition is much larger than that for the automatic condition. Noticeably, the increase is not continuous in this frequency band and begins only several minutes after the irrigation event. It suggests that the transient fluctuation is time-locked to the onset of irrigation, irrespective of its duration and amount of water, and might be a first morphological signal for the water supply; the irrigation condition only affects the strength of fluctuation.

As can be seen in Fig. 7, in contrast to the leaf inclination, fluctuation of biopotential in this band is seen even before the irrigation event and the time-frequency patterns are more complex both in the manual and automatic conditions. This presumably happens because of rapid decay of biopotential due to the sensitiveness to shortage of water. It seems, however, that after the irrigation event, the patterns of leaf inclination and biopotential are similar in both conditions. This correlation indicates that morphological changes of plants can be estimated by measuring biopotential in a specific frequency range and vice versa.

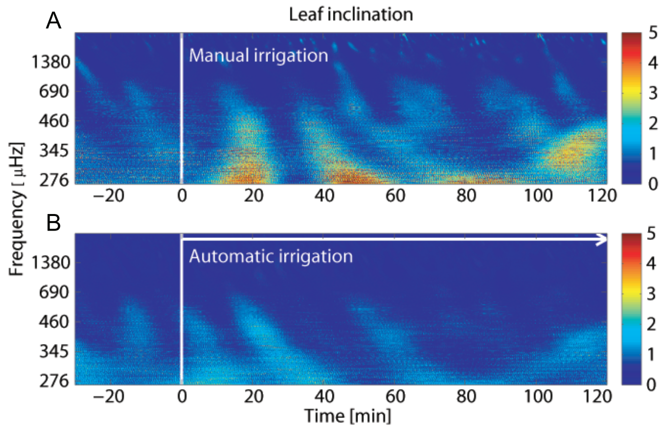

Fig. 6: Normalized wavelet power for the average leaf inclination after manual (A) and automatic (B) irrigation.

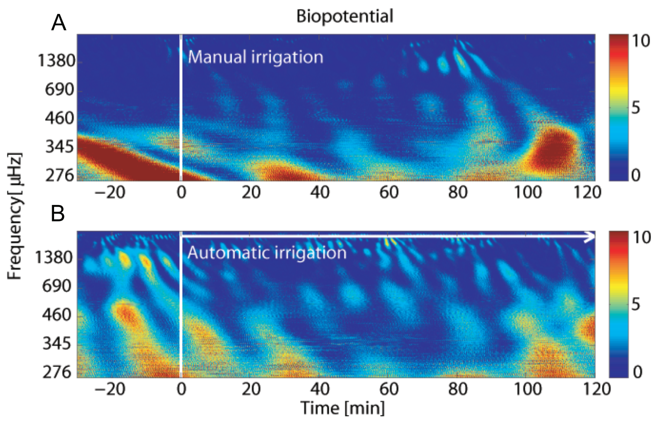

Fig. 7: Normalized wavelet power for the average biopotential after manual (A) and automatic (B) irrigation.

Eventually, further investigations remain to be done on the actual potential of these analysis results for the control in plant-machine interface.

IV. CONCLUSION & FUTURE WORK

In this paper, prompted by the potential of plant-machine interfaces, we designed a communication method by assessing the morphological and intrinsic biopotential changes of an avocado plant. First, we focused on the fact that morphological changes in the plant represented by leaf inclination were able to register the water stress in avocado plant, and

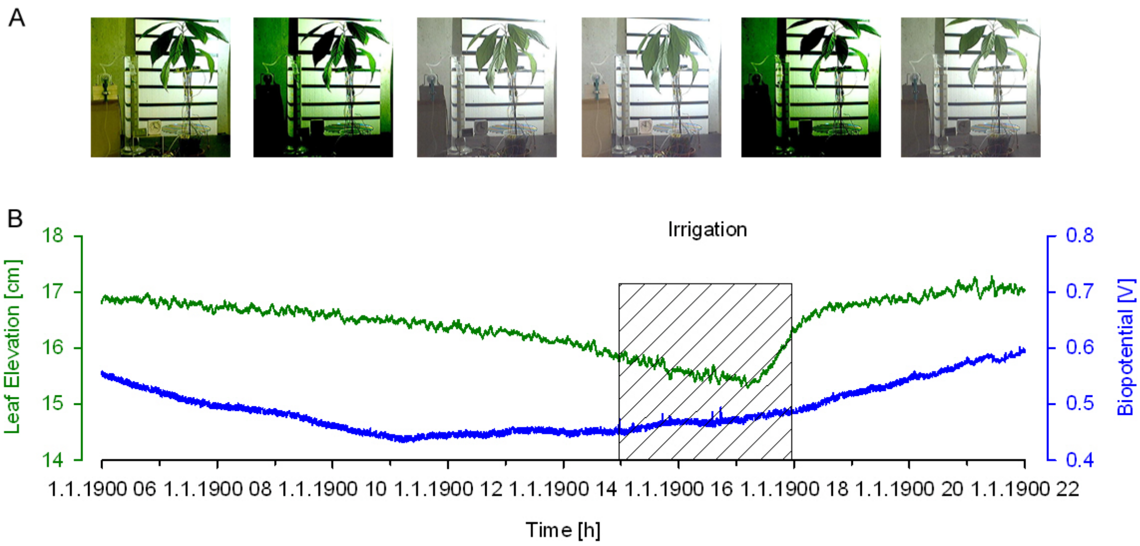

Fig. 5: (A) Time series of pictures showing morpholgical changes of an avocado plant during an automatic irrigation experiment with increased detection threshold. (B) Plot of the average leaf elevation and the biopotential during the close-loop experiment.

employ this change as a trigger signal for irrigation. Second, having noticed the prompt change of biopotential after an irrigation event, we employed it as a signal for abandoning the irrigation. Hence, by carefully assessing patterns in the leaf inclination and biopotential signals, we contrived an automated irrigation scheme to control water supply for a plant. The result of this closed interaction loop opens up possibilities for developing technologies that autonomously regulate plant resources or that may utilize the intrinsic computational capabilities of plants.

As a future work, we intend to extend our interest toward two folds; mobility and learning. We will further develop the system to become untethered such that it can rove in the environment. Moreover, we will incorporate learning mechanisms, such that a plant can optimally feed itself by regulating its resources (e.g. amount of water). Additionally, it might also become feasible to exploit the plant's own repertory of sensors to get a wide range of environmental information. This potential could even be increased by assembling a variety of plants which are adapted to different climates and therefore cover an even broader range of ambient parameters.

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REFERENCES

[1] Karban, R.: Plant behaviour and communication. Ecology letters **11** (2008) 727–739
[2] Trewavas, A.: Aspects of plant intelligence. Annals of Botany **92** (2003) 1–20
[3] Wiener, N.: Cybernetics: Or Control and Communication in the Animal and the Machine. The MIT Press (1948)
[4] Kuribayashi, S., Sakamoto, Y., Morihara, M., Tanaka, H.: Plantio: An interactive pot to augment plants' expressions. In: International Conference on Advances in Computer Entertainment Technology. (2007) 139–142
[5] Kuribayashi, S., Sakamoto, Y., Tanaka, H.: I/o plant: a tool kit for designing augmented human-plant interactions. In: Computer / Human Interaction. (2007) 2537–2542
[6] Font, L., Krsi, F., Farkas, I.: Leaf inclination based non destructive water stress indication for vegetables. In: International Conference on Sustainable Greenhouse Systems. (2004)
[7] Kopyt, M., Ton, Y., Ner, Z.B., Bachrach, A., Zieslin, N.: A trial of the phytomonitoring technique for roses. Acta Hort. **547** (2001) 205–212
[8] Gurovich, L.A., Ton, Y., Vergara, L.M.: Irrigation scheduling of avocado using phytomonitoring techniques. Ciencia e Investigacion Agraria **33(2)** (2006) 117–124
[9] Gurovich, L.A., Hermosilla, P.: Electric signalling in fruit trees in response to water applications and light-darkness conditions. Journal of Plant Physiology **166** (2009) 290–300
[10] Gil, P.M., Gurovich, L., Schaffer, B., Garca, N., Iturriaga, R.: Root to leaf electrical signaling in avocado in response to light and soil water content. Journal of Plant Physiology **165** (2008) 1070–1078
[11] Gil, P.M., Gurovich, L., Schaffer, B., Alcayagad, J., Reye, S., Iturriaga, R.: Electrical signaling, stomatal conductance, aba and ethylene content in avocado trees in response to root hypoxia. Plant Signaling & Behavior **4:2** (2009) 100–108
[12] Fromm, J., Fei, H.: Electrical signaling and gas exchange in maize plants of drying soil. Journal of Plant Physiology **132** (1998) 203–213
[13] Fromm, J., Lautner, S.: Electrical signals and their physiological significance in plants. Plant, Cell and Environment **30** (2007) 249257
[14] Correll, N., Bolger, A., Bollini, M., Charrow, B., Clayton, A., Dominguez, F., Donahue, K., Dyar, S., Johnson, L., Liu, H., Patrikalakis, A., amd M. Tanner, J.S., White, L., Rus, D.: Building a distributed robot garden. In: IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), St. Louis, MO (2009)
[15] Parkinson, K.J., Banbury, G.H.: Bio-electric potentials of intact green plants. Journal of Experimental Botany **17** (1965) 297–308
[16] http://en.wikipedia.org/wiki/Avocado
[17] Daubechies, I.: Ten lectures on wavelets. Society for Industrial and Applied Mathematics (1992)