Plants and Environmental Sensors for Smart Agriculture, an Overview

Umberto Garlando*, Lee Bar-On†, Adi Avni‡, Yosi Shacham-Diamand†, Danilo Demarchi*
Email: umberto.garlando@polito.it, lee.bar-on@mail.huji.ac.il, lpavni@tauex.tau.ac.il, yosish@tauex.tau.ac.il, danilo.demarchi@polito.it
*Department of Electronics and Telecommunications, Politecnico di Torino, Italy
†School of Electrical Engineering, Tel Aviv University, Tel Aviv, Israel
‡Faculty of Life Sciences, Tel Aviv University, Tel Aviv, Israel

***Abstract*—Smart agriculture is a fast-growing research field. From one side, the increase of the human population is always demanding more food production. On the other side, the consciousness of the importance of diet quality requires a more controlled and higher quality production, both in terms of nutrition factors and lower use of pesticides. Thus, it is straightforward to apply the progress in electronics and sensors technology for reaching these different objectives. In this paper, we present an overview of the sensors applied for smart agriculture. Two different categories are presented: sensors for evaluating plant health and fruit conditions and sensors used to monitor the environmental condition where the plants are growing.**

***Index Terms*—Agrifood, green electronics, plants, smart agriculture**

I. Introduction

With the human population's continuous growth, a big challenge for agriculture industries and farmers is coming up: how to face the exponential increase of global demand for food production? Food production must increase rapidly. However, this is not as simple as it seems because the environmental resources are limited. Therefore there is the need for new and innovative techniques aimed to maximize the efficiency of every single land sustainably, with a limited eco-footprint. On this purpose, more and more researchers are focusing their attention on the development of innovative smart farming and precision agriculture technologies.

After mechanization advent and the genetic control/modification, precision agriculture is also known as the third revolution in the history of agriculture. It refers to the utilization of automation and robotics on agricultural processes, and its main goals are to optimize the high labor costs and to improve the production efficiency, minimizing the footprint/impact on the environment. The first pillar in order to introduce the concept of automation is given by the need for data, therefore sensors. The data gathered from the sensors are used to increase the precision in all the aspects of cultivation: watering, usage of pesticides, and also fruits ripening. Furthermore, in controlled environments, like in greenhouse cultivation, it is possible to control parameters like temperature and humidity, acting directly to set the best condition for the plants.

This paper presents a brief overview of the sensors for monitoring the plants and the environment. Section II describes visual sensors and sensors able to detect volatile compounds (VOCs) emitted by the plants. In Section III, the sensors commonly used to monitor the environmental conditions (temperature, humidity, and light intensity) are presented. Furthermore, soil moisture sensors are listed in this category. Section IV, describes the idea of a combined analysis of the data coming from the presented sensors categories. Section V shows examples of sensor networks and how they are used for smart agriculture. Finally, the conclusions are collected in section VI.

II. Plant sensors

In this section, an overview of the plant's sensors is presented. We start focusing on visual sensors that are highly adopted to evaluate the ripening of fruit and plant wellness. Then, we will describe sensors to detect VOCs.

Imaging techniques for leaf samples such as [13]–[15] achieved a classification accuracy of plant diseases of 82.5%, 90%, and 92%, respectively. Besides, [16] used plant leaf images to build a deep learning model to classify diseased plants from healthy plants with a promising accuracy of 99.53%. Given these examples, different cameras working with different spectra are used together. For example, Red, Green, and Blue (RGB) and Near Infrared (NIR) imaging methods are integrated into a robot and used in synchronization to measure overall plant health using the Normalized Differential Vegetative Index (NDVI) in [12]. NDVI is an indication used by many agriculturists and scientists to measure the overall health of plants and vegetative crops. This concept comes from the fact that healthy leaves with high amounts of chlorophyll will strongly absorb visible light and strongly reflect near-infrared light. In contrast, unhealthy or stressed plants with low chlorophyll content will strongly absorb near-infrared light and reflect most of the visible light [17]. Visual data and machine learning are used in literature to monitor the crop growth stage. Authors in [23] show a machine learning algorithm that classifies tomato fruits during growth. Furthermore, an automatic notification system based on chatbot was implemented. Post-harvest disease and defects

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TABLE I
TABLE OF ETHYLENE SENSORS

Method	Type	Low cost	Mobile
Optical	1. Photoacoustic spectroscopy 2. Non-dispersive infrared (NDIR) spectroscopy 3. Turn-on fluorescence with luminescent polymers and olefin metathesis catalyst/fluorescent dye hybrid molecules	No No Yes	No No Yes
Electrical / electrochemical	1. Electro-catalytic measurement 2. Chemiresistors 3. Graphene based field-effect transistors 4. Oxidation/reduction amperometry	No Yes Yes Yes	No Yes Yes Yes
Physical	1. Miniaturized gas chromatography (GC) 2. Ion transport high field mobility MS	No No	No No

detection techniques are available. Machine learning on visual data is used to achieve high detection accuracy, as seen in [24] and [25], with a classification accuracy of fruit defects of 89.2% and 93%, respectively. Also, [26] achieved an accuracy of 96% for defect detection found in red grapefruit. However, visual sensors and cameras can be costly, and it is not very easy to cover the entire cultivation area.

Significant research efforts are invested in the study of volatile organic compounds emitted by the plants. Volatile emission is an integral part of plant development and has an essential role in plant defense and communication with other organisms. During ripening, tomato, and many other commercially important fruits, experience a rise in cellular respiration and emit relatively high CO_2 levels and the plant phytohormone ethylene, C_2H_4, in a peculiar climacteric pattern [6]. In tomato plants, these emissions are accompanied by a concerted sugar accumulation process, loss of acidity, and color change, from green to red, due to the accumulation of lycopene. Moreover, as a result of mechanical wounding or biotic attacks by insects or pathogens, tomato tissues emit peculiar volatiles, such as the ester methyl-jasmonate, ethylene, as well as mono- or sesqui- or homoterpene metabolites such as β-caryophyllene, β-phellandrene, limonene, β-pinene [7], [8]. This response is not unique to tomatoes, but it is part of a general response to plant injury in many crops. Although the levels of these volatile chemicals are minute, they can be easily detected by chromatographic and spectroscopic methods, and their monitoring can serve as a unique identifier for plant vitality or several stress conditions, as well as serving as a good indicator for the degree of fruit ripening and plant general health. Here a brief analysis of the possible sensors for detecting VOCs is reported.

A. Ethylene sensors

Recent advances in sensor miniaturization and the use of information and communication technologies lead to the development of mobile sensor units [1]–[5]. Nowadays, the available technologies for ethylene gas detection can be divided into three sub-categories, depending on the transduction implemented. The first category includes technologies based on optical principles. Either spectroscopy (photoacoustic or non-dispersive infrared, NDIR) or fluorescence are used. Another approach relies on the electrical variations induced by ethylene in the sensors. The last category takes advantage of specific physical mechanisms: gas chromatography and ion transport. These concepts are summarized in Table I, highlighting their costs and compactness.

B. Jasmonate sensors

In response to certain external stress conditions, methyl jasmonate (MeJa), a plant elicitor, also plays an important role in increasing leaf trichome density to protect the plants from insect herbivores. Additionally, the phytohormone MeJa is overproduced in the course of fruit ripening. Therefore, the monitoring of MeJa is important for the crop yield and is relevant to agricultural economies [9]–[11]. There are few possible sensors for MeJa: Electrochemical [35], [36] and chemo-fluorescent [37].

C. Impedance Sensors

A new kind of sensors that are acquiring more interest is related to impedance measurements. Authors in [18] and [27] demonstrated how impedance measurement is very effective and promising: low-power, small, simple. The first immediate indication from impedance is the general health status of the plant, in particular, if it is suffering low watering. However, crossing impedance with the other sensors, as described in [27], it is possible to have more important and detailed information. It has been demonstrated that both modulus and phase are important to be detected.

III. ENVIRONMENTAL SENSORS

Greenhouses are widely adopted to ensure the productivity of vegetables despite the atmospheric conditions. In greenhouses, it is crucial to monitor environment status for controlling in closed-loop the greenhouse parameters. In the open air, the use of environmental sensors is strategic because it gives the possibility of preventing weather damages or quickly react in case of dangerous events.

The monitoring of global environmental parameters has to include all the aspects related to the habitat where the plants are growing. Light intensity, temperature, and relative humidity are typically measured. In literature, different examples of projects capable of simultaneously measuring these three quantities exist. For example, in [18], a system for measuring the different environmental quantities is presented. Furthermore, in [12] a similar set of sensors is placed on an Unmanned Ground Vehicle (UGV), and the values extracted are used to get an accurate mapping of the greenhouse environment. The authors in [19] propose a system for monitoring the greenhouse using the ZigBee protocol. A simple mobile system capable of performing environmental measures is presented in [20]. Together with monitoring, in [21] and [22] there are examples where monitoring ad low budget electronics are used together to implement an automatic control system of the ventilation and watering in the greenhouse.

Together with environmental data, another important parameter normally monitored is soil moisture. Different sensors exist for this task. Authors in [18] propose a possible implementation using a commercial sensor, developed by IRROMETER [28]. It is a gypsum block that changes its resistive value depending on the water present in the soil where it is placed. By reading its resistance, it is possible to estimate the humidity value of the soil. Regarding sensor systems, different

Fig. 1. Watermark sensor by Irrometer

commercial products are available. For example, Grodan [29] and Meter Environment [30] propose different sensors for soil moisture and temperature, together with electrical conductivity. However, these systems are intended for medium-big greenhouses and need a cabled system. The one adopted in [18] instead is portable and could be integrated into a mobile system.

When considering these kinds of sensors, low power and wireless connection are vital factors. In fact, connection to the power grid is available, for example, inside a greenhouse, but it is more difficult in the open air. To overcome this limitation, energy harvesting is another very promising research field for smart agriculture. Different examples exist in the literature, mainly based on solar cells [31].

IV. Sensor Data Fusion

The previous sections introduced examples of different sensors available to monitor plant status and environmental conditions. However, the data obtained with those sensors can give even more information if analyzed together. Authors in [18] propose to evaluate the correlation between environmental values and plants' electrical impedance. In this way, it is possible to relate variations in plant parameters to their needs directly. Furthermore, if the variations in plant parameters are proven to be caused by external variations (temperature, soil humidity, ecc.), it is possible to act directly on the cause of the stress. Soil moisture is a crucial parameter, and its value is also used to decide when watering the crops. However, different vegetables have different water needs. Therefore, to relate the watering process on the soil moisture value could be non-optimal. Better results could be achieved, relating it directly to the changes in plant parameters. This kind of analysis seems to be promising and should be further explored in the future of smart agriculture.

V. Sensor Networks for Agriculture

Agriculture is a specific application scenario where the interconnection of sensors cannot be done applying standard methodologies. The cost of a sophisticated infrastructure is not justified, and often the areas are not covered with any network coverage.

In [32], different sensors networks are presented and analyzed. It presents both Terrestrial Wireless Sensors Networks (TWSN) and Wireless Underground Sensors Networks (WUSN). The most exciting potential applications for WSN are irrigation management, farming monitoring, disease control, and fertilizer accuracy. Different examples exist in the literature regarding the first application [38]. Precise and automatic watering is the most simple example where WSN are applied. It is possible to spread sensors for soil moisture over the fields and control with high precision the amount and the localization of the watering procedure. The same approach can be applied to pesticides and fertilizers. Sensors can be statically placed in the environment or positioned inside moving elements, like tractors. In this last configuration, it is essential to monitor also the actual position of the sensors. Also, a hybrid solution, consisting of both fixed and mobile sensors, is possible. Different communication technologies are available. While Wi-Fi has a good range, it also shows high power consumption, Bluetooth has lower consumption, but a limited range. In this field, where a small amount of data is sent over long distances, specific protocols are adopted, particularly LoRa [39] and SigFox [40].

An innovative concept is presented in [33] and [34], where the exchange of the information is done exploiting the plant itself, introducing the concept of Plant Body Communication and the setup of what is defined as the Internet of Plants. With this approach, the infrastructure is not needed, else the presence of data concentrators that can collect the information from the sensors installed in the plant and transmit them to more standard communication infrastructures.

VI. Conclusion

In this paper, we presented different kinds of sensors already adopted or with great potential in smart agriculture. With precise knowledge of the plant condition, it is possible to reduce the eco-impact of agriculture drastically. Watering only when needed and use pesticides only if really necessary can be the first step towards this direction.

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