Advances in Sensing Technologies for Smart Monitoring in Precise Agriculture

Luca Maiolo[a] and Davide Polese[b]
Istituto per la Microelettronica e Microsistemi, Consiglio Nazionale delle Ricerche, Roma, Italy

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Abstract: The demand for a continuous increment of crop production reducing at the same time the impact on the used resources is a challenge that can be solved only exploiting the full potential of sensors technology applied in precise agriculture. In this review, we present the most recent advances in remote sensing technologies to be deployed in field and in greenhouses to monitor multiple key parameters such as air temperature, solar radiation, vegetative index, plant microclimate, soil feature, etc.

1 INTRODUCTION

The improvement of crop production minimizing the efforts in terms of water, soil, nutrient reservoir represents one of the most impelling challenge in modern agriculture (Lytridis, Kadar, & Virk, 2006; Pimentel et al., 2007; Tsiafouli et al., 2015; Weiss, Jacob, & Duveiller, 2020). To this purpose, the interest in adopting innovative technologies in precise agriculture is continuously increasing.

Indeed, precise agriculture has the aim to use technology and exploit novel and integrated approaches to maximize the crop production preserving at the same time the used resources (Pierce & Nowak, 1999; Schellberg, Hill, Gerhards, Rothmund, & Braun, 2008) (see fig.1). In particular, remote sensing can be the most suitable candidate to assist this transition, allowing the monitoring of plant nutrients, the presence of pathogens and the evolution of the crop during the seasons.

Until now, remote sensing has been performed mainly by using satellite images or airborne LIDAR, however in the last years, new approaches based on Wireless Sensor Networks (WSNs) have gained interest (Cagnetti, Leccese, & Trinca, 2013; Ojha, Misra, & Singh, 2015; Polese et al., 2019). WSNs can be deployed with light infrastructures and they can be equipped with several kind of sensors in order to monitor different parameters on the plant and in the soil or in the surroundings such as temperature, humidity, CO_2 content, etc.

Due to the size of the field or in case of greenhouses a proper trade off should be taken into account to consider sensor lifetime, sensor costs and sensor deployment. Moreover, depending by the case, passive or active nodes should be conceived as valuable choice regarding the specific WSNs architecture combined with the features of the field. In particular, battery lifetime for each node or energy harvesting methods need to be considered together with the cost for device dismantling and replacement.

Figure 1: A scheme representing the new paradigm for precise agriculture: adopting smart technologies for maximizing of the yield, taking care for the environment.

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[a] https://orcid.org/0000-0003-3220-5353
[b] https://orcid.org/0000-0002-6332-5051

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In this paper, we explore different types of sensors that can be integrated into a WSN in order to estimate the state of health of the crop. The monitoring of a cultivation can be roughly divided into three main areas: at ground level, at plant level and at aerial level. Different technologies are involved in these three types of analysis, even if they can be combined to obtain a fully picture of the cultivation state at macro and microscale. A scheme with these technologies is depicted in fig.2.

In particular, in this review, in section 2 we describe the sensor used to estimate physical characteristics; in section 3, the sensors for volatile compounds; in section 4, sensors for evaluate the soil conditions; in section 5, the sensors to estimate the plant stress level; finally, in section 6, conclusion is described.

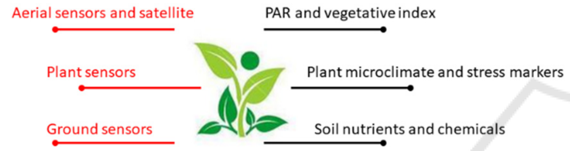

Figure 2: A scheme representing in red the technologies involved in the specific type of monitoring, in black the parameters usually detected.

2 PHYSICAL SENSORS

Air temperature and solar radiation and in particular photosynthetically-active radiation (PAR) are ones of the main factors that regulate the fruit maturation (Uzun, 2007). The variation of both parameters do not require fast sensor response, moreover, the daily mean value is more important of the instantaneous value, on the other hand, good accuracy and precision are preferred.

Regarding temperature sensors, among the multiple options (Childs, Greenwood, & Long, 2000), thermistors and platinum resistors represent the best choice even if band gap thermal sensors can be a most efficient alternative due to cheaper cost and large variety on the market. Indeed, numerous chips integrating sensors, analog-to-digital converter and standard digital communications (making these devices easily integrate in wireless nodes) are commercially available and, generally, despite a lower accuracy, less than 0.5 °C, they can fulfil many applications.

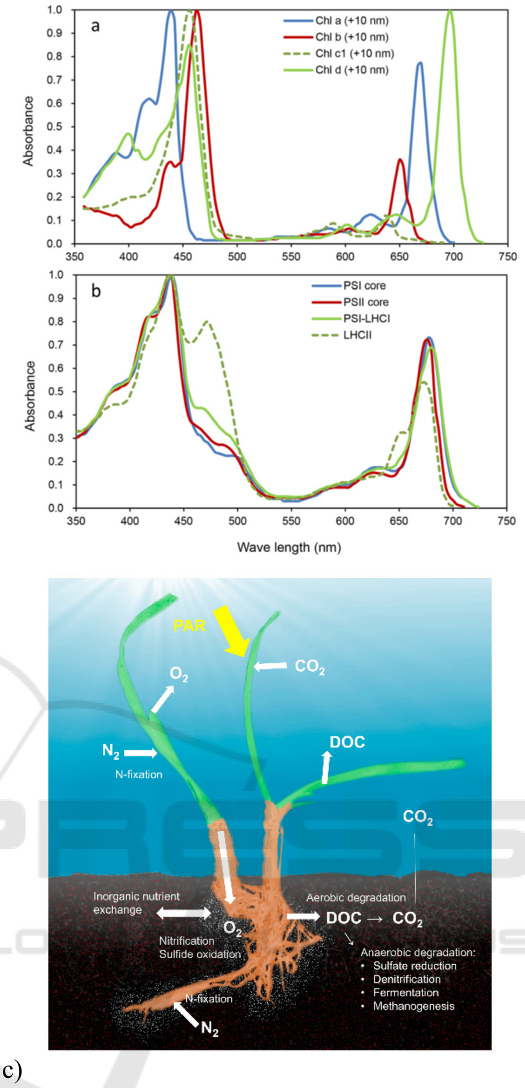

Figure 3: a) Absorbance spectra of several chlorophylls (Chl a, b, c1 and d). It is possible to see how the main absorption occurs in PAR spectrum. b) Absorbance spectra at plant photosystem level (PSI core and PSII core) and light harvesting complexes (PSI-LHCI and LHCII) where the transfer of energy and electrons happen (Reprinted from: (Kume, Akitsu, & Nasahara, 2018)). c) The effect of PAR on the different plant process. Reprinted from: (Ugarelli, Chakrabarti, Laas, & Stingl, 2017).

By definition, PAR is considered the radiation with a wavelength included in 400-700 nm range, that plants can use in the process of photosynthesis (see figure 3), even if recent studies indicate that also photons with wavelength in the range 701 to 750 nm may have a role in the plant's photosynthesis (Zhen & Bugbee, 2020). This parameter is important to roughly evaluate the state of health of a plant, since each plant exhibits a peculiar spectral band depending by the specific water content, canopy characteristics and plant form. Considering this spectrum of radiation that includes visible light and near infrared, sensors that can estimate, better if separately, both radiations should be included in every sensor node. A discrete approach with photodiodes and transimpedance amplifier guarantee more flexibility, but integrated solution, with even ADC, guarantees more compactness. Example of IC integrating both detectors and digital output are BH1730FVC from ROHM semiconductors (ROHM, 2016) and TSL2572 from AMS (AMS, 2019).

3 VOLATILE COMPOUNDS SENSORS

The changing in the composition of the atmosphere surrounding the plant represents a simple way to understand the state of health of the crop since several volatile compounds participate to plant's life. For example, carbon dioxide (CO_2) is one of the main components that sustain the plant's life (Ehlers & Goss, 2016) and Volatile Organic Compounds (VOCs) are early markers of the plant's physiological dysfunction (F. Martinelli et al., 2015).

Gas sensors have to discriminate different volatile compounds and at the same time quantify their presence. If the number of the volatile compounds is limited and a priori known, a set of selective sensors can be used, but this approach has the drawback to be not easily improvable, if new gases need to be detected and quantified other sensors has to be added. On the other hand, similar results can be obtained with a set of unselective gas sensors, following the electronic nose approach (Gardner & Bartlett, 1994; Persaud & Dodd, 1982; Röck, Barsan, & Weimar, 2008). In this section, we introduce these two different classes of sensors focusing on: selective and non-selective gas sensors.

3.1 Selective Gas Sensors

A selective gas sensor shows a dominant response respect a compounds rather than others interferes that can be both physical or chemical (D'Amico & Di Natale, 2001). The gold standard for selective gas detection is the measurements of its absorption bands in ultra-violet, visible and infra-red (IR) regions of the electromagnetic field (Hodgkinson & Tatam, 2013). If optical sensors that need of long gas cells cannot be taken into consideration for in field application, non-dispersive infrared (NDIR) optical gas sensor that use a broadband IR source together with two optical detectors, that are tuned on separate spectrum regions, to identify common pollutant could be a good candidate to be used in field applications and some example of these sensors are already on market (Alphasense, n.d.-a; Fonollosa et al., 2008; Hodgkinson & Tatam, 2013; SSTSensing, 2020). Conversely, these devices show low sensitivity, interference due to relative humidity and a limited set of detectable gases, thus limiting their feasibility to specific application (Dinh, Choi, Son, & Kim, 2016).

Other candidates as selective gas sensor are the potentiometric sensors: these devices measure the Nerst's potential created between a sensing electrode and a reference electrode separated by a solid electrolyte as consequence of the adsorption of the gas. An auxiliary electrode is often introduced to enlarge the number of detected compounds. (Pasierb & Rekas, 2009). Potentiometric gas sensors allow detecting a larger number of volatile compounds than NDIR, but the number remains limited. Example of commercial available potentiometric sensors are NO2-B43F (Alphasense, n.d.-b) or GS+4CO (Ddscientific, n.d.).

3.2 Non-selective Gas Sensors

With the electronic nose approach, it is possible to maximize the number of detectable VOCs, reducing the costs for the implementation of the sensing platform or the sensing node. Indeed, the usage of non-selective gas sensors permits to integrate similar active materials (e.g. polymers, metal oxides) with different cross sensitivity and demanding the discrimination of the VOCs mixture to a post-process computational method (Gutierrez-Osuna, 2002). This approach has been tested in different scenarios, showing good results in term of discrimination of multiple gases and odours in a real environment (Laothawornkitkul et al., 2008; F Leccese et al., 2018; Fabio Leccese et al., 2016; F. L. Marco et al., 2017; E. Martinelli et al., 2015; Pecora et al., 2009; Röck et al., 2008). One of the main advantage of this technique is related to the possibility to print the active layer with polymers or metal oxide inks directly on the substrate, reducing the manufacturing time and consequently the fabrication costs. Moreover, regarding metal oxide gas sensors, it is worth to mention the possibility of using the same sensors as multiple "virtual" sensors by temperature modulation (Hierlemann & Gutierrez-Osuna, 2008). This approach allows to discriminate different compounds using a single sensors (Herrero-Carrón, Yáñez, Rodríguez, & Varona, 2015; E. Martinelli, Polese, Catini, D'Amico, & Di Natale, 2012; Polese, Martinelli, Catini, D'Amico, & Di Natale, 2010). Nevertheless, the use of temperature modulation requires energy that is a big drawback for application in system with energy limitations. To this purpose, great efforts have been done to limit the power consumption or introduce materials that maintain sensing characteristics even at room temperature (Elmi, Zampolli, Cozzani, Mancarella, & Cardinali, 2008; Polese et al., 2015, 2017).

Finally, it is important to note that the discrimination algorithms can be implemented remotely, without providing a specific hardware on the sensing platform to run them and gas discrimination and classification can be compared and sensor nodes can be calibrated among them using appropriate algorithms (S. Marco & Gutiérrez-gálvez, 2012; Polese et al., 2013; Yan & Zhang, 2015).

3.3 Ultra-flexible Gas Sensors

The possibility to implement flexible and conformable sensors directly on the plants (e.g. on the leaves), represents a smart approach to exploit the features of flexible electronics in this specific application (Nassar, Khan, & Villalva, 2018). Indeed, flexible polymeric sensors can be light, transparent and they can be tailored in form of net to avoid any possible damage on the plant. In this way, the normal physiology of the plant is not affected and the parameters to be detected can be collected in a significant space around the plant to monitoring its microclimate (Zhao, Y, 2019). These sensors can be integrated into ultra-thin polymeric foils together with readout electronics and data pre-processing units, thus allowing the fabrication of complete sensing node.

In the recent years a lot of examples have been reported in literature to monitor a plethora of gases, pollutants and valuable parameters like pH, relative humidity and temperature (L Maiolo et al., 2014; Zampetti et al., 2009, 2011). In particular, resistive and capacitive sensors as well as potentiometric devices have been proposed (Luca Maiolo et al., 2013). Moreover, to increase analyte sensitivity and maintaining low device cost, active layer composed of polymeric or metal oxide nanostructures have been presented (Ahn et al., 2010; Chinnappan, Baskar, Baskar, Ratheesh, & Ramakrishna, 2017; Fiaschi et al., 2018; Li, Li, Wu, Wang, & Luo, 2019). Indeed, especially disordered nanostructures like metal oxide nanorods, nanowires or nanofoams together with polymeric nanofibers exhibit high sensitivity and easy fabrication process, with scalable manufacturing methods such as electrospinning technique, printed electronics or chemical bath deposition technique (Ding, Wang, Yu, & Sun, 2009; Strano et al., 2014) (see fig.4).

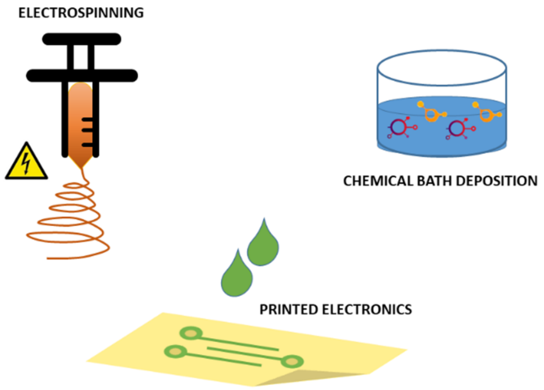

Figure 4: A scheme representing the low cost manufacturing processes used for sensors fabrication.

4 SOIL SENSORS

The soil is one of the main elements for the plant life, and its characteristics have effect on the quality and the productivity of the agriculture production. To this purpose, it is of main importance estimate the soil physical, mechanical and chemical characteristics.

Physical properties of soil takes into account colour, texture, structure, porosity, density, consistence, temperature, and air (Osman, 2013), whereas mechanical properties mainly takes into account the mechanical strength mainly due to the soil compaction that reduces the growth rates of crop roots (Adamchuk, Hummel, Morgan, & Upadhyaya, 2004). Finally, the chemical characteristics takes into account the pH and the soil nutrient mineral content. Generally, physical properties are evaluated by electrical spectroscopy, optical or radiometric sensors (Corwin & Lesch, 2005; Robinet et al., 2018; Romero-Ruiz, Linde, Keller, & Or, 2018), whereas mechanical properties are estimated by the use of cone penetrometer (Cho, Sudduth, & Chung, 2016). Finally, the soil nutrient content is estimated by ion exchange membranes (Gu & Grogan, 2020; Qian, Schoenau, & Huang, 1992).

Up to now, the use of the soil sensors in WSN is very limited if not absent, but, nevertheless, the possibility of integrating these measurements would be very interesting in improving the crop health. However, the integration of standard sensors as temperature, humidity, pH, and ion selective could be very interesting to investigate and feasible in the few next years.

5 PLANT STRESS SENSORS

The challenge of a reliable monitoring of plant growth and development relies on the possibility to individuate early stage markers of drought, pathogens and plant physiological dysfunction long before these signs become visible. Many physiological functions of the plant can be related to the abiotic or biotic stress conditions that induce the formation of reactive oxygen species (ROS) outside the cells (Qi et al., 2018). The detection of these markers should be safe and not harmful for the cultivation, preferring non-destructive probing methods like optical and remote sensing techniques.

Among others, portable Raman spectroscopy has been proposed as valuable tool to obtain a rapid quantification of the stress phenotype associated with nutrient deficiency (Gupta, Huang, Singh, & Park, 2020). This technique can be applied directly to the leaf of the plant without wasting it.

A very elegant strategy has been recently reported in literature, combining smart electrochemical sensing with biotechnology (Desagani, Jog, Avni, & Shacham-Diamand, 2020; Pandey, Teig-Sussholz, Schuster, Avni, & Shacham-Diamand, 2018). In these works, the plant itself is a living sensor. In particular, transgenic plants can be instructed to produce specific analyte and markers enabling a direct monitoring of the state of health of the plant.

This approach is part of a larger vision in which the sensors network itself is a living cultivation. In this case, the conventional of Internet of Things (IoTs) is translated into Internet of plants (Bais, Park, Weir, Callaway, & Vivanco, 2004; Checco & Polese, 2020).

6 CONCLUSIONS

In this review, we report all the innovative sensing technologies available for the optimization of the crop production in precise agriculture. The new paradigm of yield maximization combined with the preservation of the natural resources can be pursued by building innovative sensing infrastructures capable to continuously monitoring the plant microclimate, the presence of nutrients and the thread of pathogens. These technologies have nowadays the potential to offer cheaper devices with high sensitivity since they can be fabricated with modular and scalable manufacturing processes. This in turn provides WSN that can control multiple parameters and merge information from the ground, at plant level and from the sky (aerial vehicles or satellite). We believe that flexible electronics and portable spectral analysis could represent a unique toolbox capable to guarantee the foreseen results in precise agriculture taking into account a responsible use of resources.

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