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Editorial

Latest Advances in Sensor Applications in Agriculture

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Abstract: Sensor applications are impacting the everyday objects that enhance human life quality. In this special issue, the main objective was to address recent advances of sensor applications in agriculture covering a wide range of topics in this field. A total of 14 articles were published in this special issue where nine of them were research articles, two review articles and two technical notes. The main topics were soil and plant sensing, farm management and post-harvest application. Soil-sensing topics include monitoring soil moisture content, drain pipes and topsoil movement during the harrowing process while plant-sensing topics include evaluating spray drift in vineyards, thermography applications for winter wheat and tree health assessment and remote-sensing applications as well. Furthermore, farm management contributions include food systems digitalization and using archived data from plowing operations, and one article in post-harvest application in sunflower seeds.

Keywords: agricultural sensors; precision agriculture; agricultural engineering; digital farming; embedded sensors; ISO 11783; infrared thermography; remote sensing

1. Introduction

Technologies are playing an important role in the development of crop and livestock farming and have the potential to be the key drivers of sustainable intensification of agricultural systems. In particular, new sensors are now available with reduced dimensions, reduced costs and increased performance, which can be implemented and integrated in production systems, allowing an increase of data and eventually an increase of information. This is of great importance to support digital transformation, precision agriculture and smart farming, and to eventually allow a revolution in the way food is produced. In order to exploit these results, authoritative studies from the research world are still needed to support development and implementation of new solutions and best practices.

Many sensor applications have significant impact in all agricultural practices. For instance, soil moisture sensors support farmers' decisions for irrigation practices which resulted in preventing plants from drought stress and over application of irrigation. Currently, many applications from remotely sensed data are used to assess crop health, drought and yield considering the improved spatial, temporal and spectral resolution and availability of such sensors. Furthermore, the revolution in sensors, information and communications technology resulted in substantial archived data for whole-farm practices and impacted in the whole system management. Farm management is an issue that goes beyond normal everyday agricultural practice. Digital technologies are helping farmers to take more wise decisions by providing a better overview of their farm.

2. Summary of the Special Issue

After the review process, 14 out of 21 papers that were submitted to the special issue were accepted for publication. Published articles include ten research articles, two review articles and two technical notes. The topics of published articles discussed different topics related to sensors applications in soil, plant health assessment, farm management and post-harvest process. This editorial classified four sections as follows: soil-related work, plant protection in vineyards, plant health assessment, farm management using digital technologies and, finally, post-harvest application on sunflower seeds.

2.1. Soil-Related Work

2.1.1. Soil Moisture Sensing

Maintaining readily available soil moisture is an essential requirement for optimum plant growing conditions which depends on soil physical properties and surrounding environmental conditions. Several techniques were developed to determine the soil moisture content: among them are the cosmic-ray neutron based sensors which have been proposed in agriculture only in the last years and allow monitoring of wide areas, and capacitance sensors which are relatively cheap and could provide real-time soil moisture content measurements but require precise calibration. The paper by Stevanato et al. [1] titled "A Novel Cosmic-Ray Neutron Sensor for Soil Moisture Estimation over Large Areas". It introduces the development of an innovative instrument which allows estimation of soil moisture from environmental epithermal neutron counts, thanks to implementation of a composite neutron detector. A second article was authored by Nagahage et al. [2] titled "Calibration and Validation of a Low-Cost Capacitive Moisture Sensor to Integrate the Automated Soil Moisture Monitoring System". In this technical note, the capacitive soil moisture sensor model: SKU:SEN0193, DFRobot, Shanghai, China, were calibrated under laboratory conditions. The objectives for this study were to examine this sensor under laboratory conditions and integrate it with a data acquisition system. The sensor data were compared with the corresponding measurements from the traditional gravimetric method and with other calibrated sensor model: SM-200, Delta-T Devices Ltd., Cambridge, UK. Results showed that the SKU:SEN0193 sensor can help in maintaining the readily available soil moisture in indoor systems which minimize the risk of both over water application and soil moisture stress.

2.1.2. Drainage Pipes Detection

For over 30 years, a very sizeable amount of agricultural drainage pipe has been installed in the United States and nowadays some farmers need to repair or replace parts of these drain lines that are not functioning properly. For such purposes, a map of the pre-existing lines is needed and in most cases this map is no longer available. The article by Allred et al. [3] is titled "Delineation of Agricultural Drainage Pipe Patterns Using Ground Penetrating Radar Integrated with a Real-Time Kinematic Global Navigation Satellite System". In this study, the authors used a ground-penetrating radar (GPR) integrated with a real-time kinematic global navigation satellite system (RTK-GNSS) to scan and map drain pipe lines within agricultural fields. The idea behind GPR involves directing an electromagnetic radio pulse into the subsurface that reflects partially off a buried feature and by measuring the elapsed time taken, the GPR can detect the depth of targeted objects. A GPR system manufactured by Sensors and Software Inc. (Mississagua, ON, Canada) was used at a central frequency of 250 MHz as recommended by previous studies [4,5] for detecting buried drainage pipes. In order to collect RTK GNSS coordinates, a system consisting of a rover receiver and base station receiver manufactured by Topcon Corporation (Itabashi, Japan) was utilized. Authors tested this system in three different sites where two sites located in Maryland and the third site located in Ohio, USA. GPR settings were adjusted to 5cm distance between signal trace measurements while the depth of investigation was 2 m at sites located in Maryland and 1.5 m at the Ohio site. Results revealed that GPR-RTK/GNSS system could successfully determine drainage pipe lines in all test sites. The detected drainage patterns were in different shapes such as: rectangular, herringbone and random lines in the tested sites. Authors recommended this system as it is faster and causes no pipe damage compared to traditional excavation methods.

2.1.3. Seedbed Preparation

After the application of primary tillage operation, soil surface still needs a secondary tillage operation such as rotary harrow to smooth soil surface and prepare suitable seedbed. Harrowing contributes to soil erosion and many techniques were used to monitor soil movement during tillage operations such as: plastic beads, granite rocks and aluminium cubes. An article by Kayad et al. [6] titled "Assessing Topsoil Movement in Rotary Harrowing Process by RFID (Radio-Frequency Identification) Technique". In this technical note, authors suggested to use RFID systems for assessing topsoil movement after rotary harrowing field trials. The RFID system consists of small RFID tags to be attached to targeted objects and RFID reader that identifies tags. The authors inserted RFID tags inside cork stoppers which have durable material and mostly simulate crop residues such as dry corn stems or corncob. The RFID tags were distributed regularly in soil and after the harrowing operation, the displacement of each tag was measured. Field trials include different working conditions of the rotary harrow such as: tillage depth, forward speed and levelling bar. Authors reported that using RFID system was a proper method for such evaluation and might have further promising application due to its robustness in simulating different materials.

2.2. Plant Rotection in Vineyards

2.2.1. Spray Drift Evaluation

A research article is by Bourodimos et al. [7] is titled "Development and Field Evaluation of a Spray Drift Risk Assessment Tool for Vineyard Spraying Application". This article starts by describing the negative points of spray drift that are caused by sprayers during the application of plant protection chemicals. Such spray drift is an important cause of environmental pollution and may lead to health risk for farm workers and animals. The objective of this contribution was to evaluate spray drift in vineyards using a drift risk assessment model developed in the framework the framework of the TOPPS-Prowadis project [8]. This model assesses the spray drift by sprayer under specific meteorological conditions such as air relative humidity, temperature, wind speed and direction. Field trials in the vineyard of Agricultural University of Athens were used to evaluate the reliability of this model by assessing ground and airborne spray drift under certain meteorological conditions. Results proved that there are significant differences in both ground and airborne spray drift among different field treatments. This study highlights that fine-tuning of spraying condition limits support farmers to spray their fields with limited spray drift, improving spray efficiency and reducing the environmental impact.

2.2.2. Weeding Robot

Weeds could be the cause of up to 40% of yield reduction [9,10] and chemical herbicides have a harmful environmental impact which proves the importance of mechanical weeding as a promising alternative. Weeding robots can improve work quality, resources management, labor efficiency and reduce energy consumption [11]. The article by Reiser et al. [12] is titled "Development of an Autonomous Electric Robot Implement for Intra-Row Weeding in Vineyards". This article reports about developing and testing the performance of a rotating electrical tiller weeder to be used for intra-row weeding automatically in vineyards. The developed robot consists of an electric tiller head rotary weeder cultivator designed and manufactured by the University of Hohenheim, Germany and mounted to an autonomous robot called "phoenix" by Caterpillar. The robot is equipped with a 2D laser scanner to follow the tree and vine rows in the front of the vehicle and four security switches for emergency cases. For controlling and recording robot data an open-source robot operating system called ROS Indigo-middleware [13] was used. The developed robot was tested in both indoor at the soil bin laboratory and outdoor at the vineyard of Hohenheim university. Performance for trunk detection were evaluated using two different methods of feeler and sonar where both of them performed well and did not harm any trunks. Moreover, the laser scanner enabled the machine to follow the rows accurately and the overall evaluation proved the ability of the developed robot for intra-row weeding which could save the energy and time of workers.

2.3. Plant Health Assessment

2.3.1. Thermography for Tree Health Assessment

Trees have many benefits to human and environment such as; prevention of desertification and global warming, ecosystems balance and human well-being. In contrast, the probability of trees or branches falling is prone to the risk of damage to people and civil infrastructures especially when trees suffer from defects compromising their health. Monitoring trees health status is essential to evaluate their biological viability, associated risks and support decision making about trees. The eleventh article by Vidal and Pitarma [14] titled "Infrared Thermography Applied to Tree Health Assessment: A Review". In this article, authors reviewed previous studies concerning the effectiveness of thermography in tree health inspection. This review was compiled taking the advantage of several research databases such as Google Scholar, ScienceDirect, Scopus and other databases in Portuguese, English and Spanish languages between October 2018 and February 2019. Authors used several keywords and combinations to select relevant articles followed by classification and filtering for duplicated references resulting in 81 selected papers. The article consists of seven sections starting with an introduction and review methodology then discussing the importance of trees and their associated risks and some methods and techniques for tree inspection. In Section 5, authors reviewed the application of infrared thermography to trees as a non-destructive inspection technique followed by conclusion and recommendations. This article highlighted the efficiency of using infrared thermography in early detection of damages in trees compared to other methods in terms of differentiating between functional and dysfunctional tissues and subsequently evaluating the vitality and health status of trees.

Tree health status verification uses invasive and destructive techniques which interfere with tree structure [15]. It is always recommended to start tree inspection with less-invasive techniques if needed to minimize the damage in the tree [16]. Another research article by Pitarma et al. [17] is titled "Contribution to Trees Health Assessment Using Infrared Thermography". This article focuses on infrared thermography application in trees inspection by using thermograms to differentiate between deteriorated and healthy tissues to observe trees as a functional whole body. Such application is well-established in different fields especially for industrial applications while it is still relatively recent in assessing tree health [16]. The main goal of this study is to provide a qualitative analysis of two different arboreal species based on differences of its thermal images. The two arboreal species are *Quercus pyrenaica* Willd and *Olea europaea* L., and thermal images were acquired by a FLIR T1030sc camera while atmospheric temperature and relative humidity were measured by the thermohygrometer FLIR MR 176. The authors recorded the thermograms at different times along the day besides taking photographs to support the visual inspection then correlating thermal patterns with tree health. Results proved the high potential of the thermography technique for tree inspection which allows early diagnosis of damage and subsequently advances tree maintenance.

2.3.2. Winter Wheat

Fungal infection symptoms usually appear on plants after a period of time according to temperature and humidity conditions and early detection and diagnosis allow farmers to protect the crop before widespread [18]. The article by Wang et al. [19] is titled "Early Detection of *Zymoseptoria tritici* in Winter Wheat by Infrared Thermography". This study reports an application for infrared thermography to detect the fungal infection by *Z. tritici* in winter wheat crop. The idea behind this application is that plant photosynthesis and transpiration are influenced by *Z. tritici* which led to a change in canopy temperature that could be detected through thermography. The objective of this study was to detect this disease early before the visual symptoms appear on the crop. Twenty-five wheat varieties were tested in a field located in Stuttgart, Germany through a split-plot design experiment. The seeds were sown on 6 October 2011 and part of plants presenting all tested varieties were inoculated artificially on 21 May 2012. Thermal images were acquired by an infrared camera (VarioCAM, InfraTec GmbH, Dresden, Germany) starting from five days before inoculation until 38 days after inoculation. Also, visual scoring was undertaken by experienced staff and all collected data were analysed using SPSS software. Results showed that in some varieties the earliest disease symptoms could be detected as early as three days after inoculation through thermography while first visual symptoms appeared after 23 days from inoculation. This application highlights the usefulness of thermography for high throughput to improve fungal disease monitoring which could help breeders in selecting disease-resistant varieties.

Several studies on spectral data applications in field crops are available from remote and ground sensors using data-mining techniques for nitrogen status and grain yield [20,21]. Most of these studies were based on measurements acquired by one sensor and there is a lack of available information on how different combinations of sensors are informative. The article by Zecha et al. [22] is titled "Utilisation of Ground and Airborne Optical Sensors for Nitrogen Level Identification and Yield Prediction in Wheat". In this study, an investigation on different fields planted with winter wheat using different nitrogen levels were done through different spectral sensors. The final goal was to test different spectral sensors on field trials conditions and to answer three main questions; How do these sensors perform in field scale? Which calculated features are significant in assessing yield, biomass and nitrogen status? How can sensors' data fusion support farmers' decisions? The investigations took place at different fields related to the University of Hohenheim, Germany where different rates of nitrogen applied within fields between 2011 and 2012. Three ground sensors where two were passive spectrometer sensors and one active fluorescence sensor were mounted on a self propelled carrier. Furthermore, a passive spectrometer mounted on a fixed-wing unmanned aerial vehicle (UAV) to acquire aerial images. All sensors data were processed in form of indices and ratios and correlated with field information and biological parameters such as wheat yield, biomass, leaf area index and available nitrogen using the R statistical software. Results revealed that more robust and higher correlations were obtained from models developed through mixed features from different sensors. Authors suggested that advanced algorithms which consider ambient solar radiation, aerial images, soil electrical conductivity and scoring may result in better yield predictions.

2.3.3. Remote Sensing of Date Palm

Many researchers investigated the possibility of using hyperspectral or thermal imagery for date palm health assessment, however, most of these studies are separate studies. An article by Mulley et al. [23] is titled "High-Resolution Multisensor Remote Sensing to Support Date Palm Farm Management". In this study, authors assessed date palm health using several sensors such as: light detection and ranging (LiDAR), visual red-green-blue (RGB), thermal and hyperspectral images. The ultimate goal for this study was to explore the most proper sensor and indicator for stress detection on date palm plants at different spatial levels. The investigations took place in a 168.8 ha date palm farm located in Al-kharj region in Saudi Arabia divided as rectangular shaped blocks of approximately 10 ha each. This farm has continuous maintenance and irrigation practices and is relatively well managed. The farm manager provided authors with archived records of red palm weevil (*Rhynchophorus ferrugineus*) infestations plus visual assessment to investigate the homogeneity of the canopy area which was considered as an indicator for healthy and unhealthy groups. Furthermore, individual tree analysis was performed from different blocks as well. The ground and the different sources of remotely sensed data were analysed using several statistical, imagery and geographical information systems software at both block and tree levels. Results showed that remote-sensing data could aid plantation management of date palm and provide insight for further site-specific management practices. Finally, authors recommended time-series analysis approach to detect changes in vegetation reflectance properties as an indicator for date palm health and suggested other future interesting topics about exploring within-block parcels to be classified as management zones for the adoption of precision agriculture techniques.

2.4. Farm Management Using Digital Technologies

2.4.1. Plowing Operation Archived Data

Embedded sensors on agricultural machinery that are used for proper diagnostics and communication can also reveal a lot of information regarding the operated tasks. There are many different sensor applications for agricultural equipment that generate huge data sets to monitor machine performance, measure and count agricultural inputs and yield. Currently, these data are combined with GNSS sensors for site specific management practices, and also due to their reduced price this allows archiving data and operations with position references. The article by Heiß et al. [24] is titled "Determination of Cultivated Area, Field Boundary and Overlapping for A Plowing Operation Using ISO 11783 Communication and D-GNSS Position Data". In this study, authors developed an algorithm that deals with georeferenced data recorded during plowing operation in order to calculate different area-related parameters in an automated way. Data were recorded by data logger GL2000 CAN-Bus (Vector Informatik GmbH, Stuttgart, Germany) connected to the diagnostic interface of the tractor used. Recorded data were the wheel-based machine speed and the differential GNSS (D-GNSS) coordinates as well as their timestamps. The MATLAB R2016b (The MathWorks Inc., Natick, MA, USA) software was used to analyse this data through different filtering equations to identify passes and subsequently determine field cultivated area, boundaries and the overlaps between the cultivated tracks. The developed algorithm could detect 58 passes which matched with the number of lifting and lowering points indicating the algorithm s functionality. Furthermore, different common indicators were calculated for the overlapping, cultivated area was quantified and field boundary was detected proving the plausibility of the results. Authors recommended this algorithm for applications such as documenting and invoicing of agricultural tasks and using overlapping analysis as an indicator of efficiency.

2.4.2. Food System Digitalization

Food security is a key factor to develop overall human well-being and human security [25]. The review article by Raheem et al. [26] is titled "Food System Digitalization as a Means to Promote Food and Nutrition Security in the Barents Region". In the Barents region, traditional food includes potatoes, meat, fish, berries and a wide range of dairy products where mostly the processing of these foods is undertaken by small and medium enterprises for better preservation and distribution. Digitalization can improve the added value to traditional food in terms of; improving harvesting process, increasing production, reducing waste and enhancing storage and distribution process. For instance, sensors and data processing applications in food system digitalization are expected to improve prediction accuracy for food value chains in the Barents region. The main objectives for this review article were to identify challenges, improve the sustainability and support for food system digitalization. The article consists of seven sections starting with an introduction then describing the current situation in the Barents region regarding climate change, human activities and food system digitalization until section number 3. From Section 4, authors discussed the role and impact of different digital technologies in food-system components and sustainability followed by future implications for the Barents region and conclusion. This review could help in conceptualizing a framework for food system digitalization and better inform both policy makers and stakeholders in the study region to support food security.

2.5. Post-Harvest Application on Sunflower Seeds

A sunflower drying process is a typical requirement for safe storage where excessive moisture levels may lead to dry matter losses and increase the activity of microorganisms. The article by Munder et al. [27] is titled "Acquisition of Sorption and Drying Data with Embedded Devices: Improving Standard Models for High Oleic Sunflower Seeds by Continuous Measurements in Dynamic Systems". In this study, innovative methods to determine sorption and drying data were used at common temperature during the handling process of agricultural products. The main goal was to develop a robust drying model for high oleic sunflower seeds based on data from sorption and drying experiments. Laboratory experiments were performed to determine a broad set of equilibrium moisture content data through gravimetric analyzer and to collect single-layer drying kinetic data at different drying conditions. The collected data were used for the development of a generalized single-layer drying model according to air conditions. The embedded systems used for this study allowed a large amount of experimental data to be recorded which were used to fit semi-empirical and analytical sorption and drying models. Results showed that the equilibrium moisture content increased at high values of water activity through sorption experiments. This study reported an appropriate model for high oleic sunflower seeds that describes the drying process for a wide range of humidity and temperatures conditions.

3. Conclusions

This special issue covers a broad range of sensor applications in agriculture and presents some of the recent research results in this topic. Author contributions include applications in soil and plant sensing, farm management and post-harvest application. The articles published in this special issue are considered an addition to the scientific community, and the editors believe that it may stimulate further ideas and new applications for sensors in agriculture.

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