RECENT BREAKTHROUGHS IN AGRICULTURAL SENSOR UTILIZATION

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Abstract:

Sensor applications are revolutionizing everyday objects, enhancing the quality of human life. In this special issue, our primary goal was to explore recent advancements in sensor applications within the field of agriculture, encompassing a diverse range of topics. This special issue comprises a total of 14 articles, including nine research articles, two review articles, and two technical notes. The key areas of focus include soil and plant sensing, farm management, and post-harvest applications. Soil-sensing topics encompass the monitoring of soil moisture content, drainage pipe tracking, and topsoil movement during harrowing processes. Plant-sensing topics involve the assessment of spray drift in vineyards, thermography applications for winter wheat and tree health assessment, as well as remote sensing applications. Additionally, contributions in farm management explore the digitalization of food systems and the utilization of archived data from plowing operations. Lastly, one article delves into post-harvest applications in sunflower seeds.

Keywords:

Agricultural sensors; precision agriculture; agricultural engineering; digital farming; embedded sensors; remote sensing.

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1. Introduction;

Technological advancements play a pivotal role in advancing crop and livestock farming, potentially serving as the driving force behind the sustainable intensification of agricultural systems. Notably, the emergence of compact, cost-effective, and high-performance sensors has opened up new avenues for their integration into production systems. This integration promises to amplify the volume of data and, consequently, the depth of information available. This transformation is crucial for supporting the realms of digital transformation, precision agriculture, and smart farming, ultimately revolutionizing the way we produce food. To fully harness these possibilities, the research community must continue to produce authoritative studies that facilitate the development and implementation of innovative solutions and best practices.

Sensor applications have already exhibited substantial impacts across various facets of agriculture. For example, soil moisture sensors aid farmers in making informed decisions regarding irrigation practices, there by averting both drought-related stress on plants and excessive irrigation. Presently, a multitude of applications harness remotely sensed data to assess crop health, drought conditions, and yield, thanks to the enhanced spatial, temporal, and spectral resolutions offered by these sensors. Moreover, the revolution in sensor technology, coupled with advancements in information and communications technology, has generated a wealth of archived data that profoundly influences comprehensive farm management. Farm management, extending beyond conventional agricultural practices, is being empowered by digital technologies, providing farmers with valuable insights to make more informed decisions about their operations.

2. Special Issue Overview;

Following a thorough review process, 14 out of the 21 papers submitted to this special issue were deemed suitable for publication. These published articles comprise ten research articles, two review articles, and two technical notes, collectively addressing diverse aspects of sensor applications. The articles delve into topics such as soil analysis, plant health assessment, farm management with the integration of digital technologies, and post-harvest processes. This editorial has organized the content into four distinct sections: soil-related research, safeguarding plants in vineyards, evaluating plant health, farm management through digital technologies, and lastly, exploring post-harvest applications in sunflower seeds.

2.1. Soil-Related Work;

2.1.1 Soil Moisture Sensing;

Sustaining optimal soil moisture levels is a fundamental requirement for promoting ideal conditions for plant growth, a factor influenced by both soil physical characteristics and the surrounding environmental variables. Various techniques have been devised for gauging soil moisture content. Among these, recent agricultural innovations include cosmic-ray neutron-based sensors, which enable the monitoring of expansive areas, and capacitance sensors, known for their cost-effectiveness and potential for real-time soil moisture measurements, albeit requiring precise calibration.

In their paper, titled "A Novel Cosmic-Ray Neutron Sensor for Soil Moisture Estimation over Large Areas," Stevanato et al. [1] present an innovative instrument that estimates soil moisture levels using environmental epithermal neutron counts. This achievement is made possible through the incorporation of a composite neutron detector.

In a complementary technical note, authored by Nagahage et al. [2] and titled "Calibration and Validation of a Low-Cost Capacitive Moisture Sensor for Integration into an Automated Soil Moisture Monitoring System," the capacitive soil moisture sensor model SKU:SEN0193 from DFRobot, Shanghai, China, undergoes laboratory calibration. This study aimed to assess the sensor's performance under controlled conditions and integrate it into a data acquisition system. The sensor's data is then compared to measurements obtained through the traditional gravimetric method and another calibrated sensor model, SM-200 from Delta-T Devices Ltd., Cambridge, UK. The results demonstrate the SKU:SEN0193 sensor's effectiveness in maintaining optimal soil moisture levels in indoor systems, reducing the risks associated with both excessive watering and soil moisture stress.

2.1.2 Detection of Drainage Pipes;

Over the past three decades, a substantial network of agricultural drainage pipes has been installed in the United States. Today, many farmers face the challenge of repairing or replacing segments of these drainage systems that have fallen into disrepair. To address this, an accurate map of the existing drain lines is essential. However, in most cases, these maps are no longer available.

In their article titled "Delineation of Agricultural Drainage Pipe Patterns Using Ground Penetrating Radar Integrated with a Real-Time Kinematic Global Navigation Satellite System," Allred et al. [3] present a novel approach. They employ ground-penetrating radar (GPR) integrated with a real-time kinematic global navigation satellite system (RTK-GNSS) to scan and map drainage pipe networks within agricultural fields. The concept behind GPR involves emitting an electromagnetic radio pulse into the subsurface, which partially reflects off buried features. By measuring the time it takes for these reflections, the GPR can accurately determine the depth of the targeted objects.

The GPR system utilized in this study was manufactured by Sensors and Software Inc. (Mississauga, ON, Canada) and operated at a central frequency of 250 MHz, following the recommendations from previous studies [4,5] for detecting buried drainage pipes. To collect RTK GNSS coordinates, a system comprising both a rover receiver and a base station receiver, manufactured by Topcon Corporation (Itabashi, Japan), was employed. The authors conducted tests at three distinct sites: two in Maryland and one in Ohio, USA.

The GPR settings were configured with a 5cm distance between signal trace measurements, with a depth of investigation set at 2 m for the Maryland sites and 1.5 m for the Ohio site. The results demonstrated the GPR-RTK/GNSS system's ability to accurately identify drainage pipe networks across all test sites. These patterns included various shapes, such as rectangular, herringbone, and random configurations. The authors endorse this system due to its speed and non-destructive nature, contrasting it with traditional excavation methods.

2.1.3 Seedbed Preparation;

Following the initial primary tillage operation, the soil surface often requires a secondary tillage step, such as rotary harrowing, to achieve a smooth and suitable seedbed. However, rotary harrowing can contribute to soil erosion. Various techniques have been employed to monitor soil movement during these tillage operations, including the use of plastic beads, granite rocks, and aluminum cubes.

In their technical note titled "Assessing Topsoil Movement in the Rotary Harrowing Process Using RFID (Radio-Frequency Identification) Technique," Kayad et al. [6] propose the use of RFID systems to evaluate topsoil displacement following rotary harrowing field trials. The RFID system comprises small RFID tags affixed to specific objects and an RFID reader that identifies these tags. The authors embedded RFID tags within cork stoppers, known for their durability and their capacity to mimic crop residues, such as dry corn stems or corncobs. These RFID tags were systematically distributed within the soil, and after the harrowing operation, the displacement of each tag was measured.

The field trials encompassed various rotary harrow working conditions, including tillage depth, forward speed, and the use of a leveling bar. The authors reported that employing the RFID system proved to be a suitable method for evaluating topsoil movement and held promise for broader applications, owing to its ability to effectively simulate different materials and its robustness.

2.2. Plant Rotection in Vineyeards;

2.2.1 Assessment of Spray Drift;

In a research article authored by Bourodimos et al. [7], titled "Development and Field Evaluation of a Spray Drift Risk Assessment Tool for Vineyard Spraying Applications," the detrimental effects of spray drift caused by sprayers during the application of plant protection chemicals are discussed. Spray drift poses a significant environmental pollution concern and may also pose health risks to farm workers and animals. The primary goal of this study was to assess spray drift in vineyards by utilizing a drift risk assessment model developed as part of the TOPPS-Prowadis project [8]. This model evaluates spray drift generated by sprayers under specific meteorological conditions, including parameters such as air relative humidity, temperature, wind speed, and direction.

Field trials were conducted in the vineyard of the Agricultural University of Athens to evaluate the reliability of this model by examining both ground and airborne spray drift under specific meteorological conditions. The results indicated significant variations in ground and airborne spray drift among different field treatments. This study underscores the importance of fine-tuning spraying conditions to enable farmers to apply their treatments with minimal spray drift, ultimately enhancing spray efficiency and reducing environmental impacts.

2.2.2 Automated Weeding Robot;

Weeds can be responsible for yield reductions of up to 40% [9,10], and the harmful environmental impact of chemical herbicides underscores the significance of mechanical weeding as a promising alternative. Weeding robots have the potential to enhance work quality, optimize resource management, improve labor efficiency, and reduce energy consumption [11].

In the article authored by Reiser et al. [12], titled "Development of an Autonomous Electric Robot Implement for Intra-Row Weeding in Vineyards," the development and performance testing of an automated electric tiller weeder for intra-row weeding in vineyards are discussed. This innovative robot comprises an electric tiller head rotary weeder cultivator, designed and manufactured by the University of Hohenheim, Germany, and integrated with an autonomous robot named "Phoenix" by Caterpillar. The robot is equipped with a 2D laser scanner to track tree and vine rows at the front of the vehicle and incorporates four emergency security switches.

To control and record robot data, an open-source robot operating system called ROS Indigo-middleware [13] was utilized. The developed robot underwent testing both indoors, in a soil bin laboratory, and outdoors, within the vineyard of Hohenheim University. The performance evaluation included trunk detection using two distinct methods: feeler and sonar, both of which demonstrated effective results without causing any harm to the trunks. Additionally, the laser scanner enabled precise row following. The comprehensive assessment affirmed the capability of the developed robot for intra-row weeding, offering potential energy and time savings for agricultural workers.

2.3. Plant Health Assessment;

2.3.1 Infrared Thermography for Assessing Tree Health;

Trees play a vital role in the environment, contributing to the prevention of desertification, mitigation of global warming, ecosystem balance, and human well-being. However, the risk of trees or branches falling poses potential danger to people and civil infrastructure, particularly when trees suffer from health issues or defects. Monitoring the health of trees is essential for assessing their biological viability, associated risks, and aiding decision-making regarding their maintenance. The eleventh article by Vidal and Pitarma [14], titled "Infrared Thermography Applied to Tree Health Assessment: A Review," explores the effectiveness of thermography in tree health assessment.

In this comprehensive review, the authors examined previous studies that investigated the utility of thermography in inspecting tree health. They conducted this review by drawing upon various research databases, including Google Scholar, ScienceDirect, Scopus, and other databases in Portuguese, English, and Spanish languages, spanning from October 2018 to February 2019. Employing a range of keywords and combinations, they selected relevant articles, classified them, and filtered out duplicates, ultimately identifying 81 selected papers. The article is structured into seven sections, commencing with an introduction and review methodology, followed by discussions on the significance of trees, associated risks, and various methods and techniques for tree inspection.

In Section 5, the authors delve into the application of infrared thermography as a non-destructive inspection technique for trees. The article concludes with recommendations and highlights the efficiency of infrared thermography in the early detection of tree damage compared to other methods. It emphasizes its ability to differentiate between functional and dysfunctional tree tissues, thereby evaluating the vitality and health status of trees without resorting to invasive and destructive techniques, which can interfere with the tree's structure [15].

For tree inspections, it is advisable to commence with less invasive techniques when feasible to minimize damage to the tree [16]. Another research article by Pitarma et al. [17], titled "Contribution to Tree Health Assessment Using Infrared Thermography," focuses on the application of infrared thermography in tree inspections. It employs thermograms to distinguish between deteriorated and healthy tree tissues, allowing for the observation of trees as functional entities.

While infrared thermography is well-established in various industrial applications, its use in assessing tree health is relatively recent. The primary objective of this study is to provide a qualitative analysis of two different tree species, namely Quercus pyrenaica Willd and Olea europaea L., based on differences in their thermal images. Thermal images were captured using a FLIR T1030sc camera, while atmospheric temperature and relative humidity were concurrently measured using the thermohygrometer FLIR MR 176. The authors recorded thermograms at different times throughout the day, supplemented by photographs to support visual inspections. The results underscore the significant potential of thermography as a valuable technique for tree inspection, enabling the early diagnosis of damage and facilitating advanced tree maintenance practices.

2.3.2 Winter Wheat;

Fungal infections in plants typically manifest over time, influenced by temperature and humidity conditions. Early detection and diagnosis are crucial for farmers to safeguard their crops from widespread damage [18]. Wang et al. [19] explore the application of infrared thermography to identify early signs of fungal infection by Zymoseptoria tritici in winter wheat crops. The underlying concept hinges on the impact of Z. tritici on plant photosynthesis and transpiration, resulting in changes in canopy temperature that can be detected through thermography. The primary objective of this study was to identify the disease before visible symptoms emerged. The experiment involved testing 25 wheat varieties in a field located in Stuttgart, Germany, employing a split-plot design. Seeds were sown on October 6, 2011, and some of the plants from all tested varieties were artificially inoculated on May 21, 2012. Thermal images were captured using an infrared camera (VarioCAM, InfraTec GmbH, Dresden, Germany) starting five days before inoculation until 38 days after. Additionally, visual scoring was conducted by experienced personnel, and all collected data were analyzed using SPSS software.

The results demonstrated that in certain varieties, early disease symptoms could be detected as soon as three days after inoculation through thermography, while the first visible symptoms appeared after 23 days. This application underscores the potential of thermography for high-throughput fungal disease monitoring, offering valuable support for breeders in selecting disease-resistant wheat varieties.

Several studies have explored spectral data applications in field crops using remote and ground sensors, applying data-mining techniques for assessing nitrogen levels and grain yield [20,21]. Most of these studies relied on measurements obtained from single sensors, leaving a gap in understanding the informative power of different sensor combinations. Zecha et al. [22] address this issue in their article titled "Utilisation of Ground and Airborne Optical Sensors for Nitrogen Level Identification and Yield Prediction in Wheat." This study investigates fields planted with winter wheat under various nitrogen levels using different spectral sensors. The ultimate aim was to evaluate the performance of these spectral sensors under field conditions and address three main questions: How do these sensors perform at the field scale? Which calculated features are crucial for assessing yield, biomass, and nitrogen status? How can data fusion from multiple sensors aid farmers in decision-making?

The investigations were conducted in different fields associated with the University of Hohenheim, Germany, where various nitrogen rates were applied between 2011 and 2012. Three ground sensors, including two passive spectrometer sensors and one active fluorescence sensor, were mounted on a self-propelled carrier. Additionally, a passive spectrometer was mounted on a fixed-wing unmanned aerial vehicle (UAV) to capture aerial images. The data from all sensors were processed into indices and ratios, which were then correlated with field information and biological parameters such as wheat yield, biomass, leaf area index, and available nitrogen, using the R statistical software.

The findings indicated that more robust and higher correlations were achieved with models that integrated features from various sensors. The authors suggest that advanced algorithms, which take into account factors like ambient solar radiation, aerial images, soil electrical conductivity, and scoring, could yield improved yield predictions.

2.3.3 Remote Sensing for Date Palm Assessment;

Numerous researchers have explored the potential of hyperspectral or thermal imagery for assessing the health of date palm trees, albeit often as independent investigations. Mulley et al. [23] contribute to this field with their article titled "High-Resolution Multisensor Remote Sensing to Support Date Palm Farm Management." In this study, the authors undertook an evaluation of date palm health using multiple sensors, including light detection and ranging (LiDAR), visual red-green-blue (RGB), thermal, and hyperspectral imaging. The overarching objective was to determine the most suitable sensor and indicator for detecting stress in date palm trees at various spatial levels.

The study was conducted in a 168.8-hectare date palm farm located in the Al-kharj region of Saudi Arabia, divided into rectangular-shaped blocks of approximately 10 hectares each. This well-maintained farm was subject to regular irrigation practices. The farm manager provided the authors with archived records of red palm weevil (Rhynchophorus ferrugineus) infestations and conducted visual assessments to examine the uniformity of the canopy area, considered an indicator for distinguishing between healthy and unhealthy groups of date palm trees. Additionally, individual tree analyses were conducted across different blocks.

Both ground-based and remotely sensed data sources were analyzed using various statistical, imagery, and geographical information systems software at both the block and tree levels. The results highlighted the potential of remote sensing data in supporting the management of date palm plantations, offering insights for site-specific management practices. The authors recommended the use of a time-series analysis approach to detect changes in vegetation reflectance properties as an indicator of date palm health. They also suggested exploring the classification of within-block parcels as management zones to facilitate the adoption of precision agriculture techniques.

2.4 Digital Technology in Agricultural Management;

2.4.1 Archived Data from Plowing Operations;

Embedded sensors within agricultural machinery, designed for diagnostics and communication, can provide valuable insights into the tasks performed. Various sensor applications on agricultural equipment generate extensive datasets for monitoring machine performance, quantifying agricultural inputs, and measuring yield. Presently, these datasets are combined with GNSS (Global Navigation Satellite System) sensors to facilitate site-specific management practices. The declining costs of these sensors also make it feasible to archive data along with positional references.

In the article authored by Heiß et al. [24], titled "Determination of Cultivated Area, Field Boundary, and Overlapping in Plowing Operations Using ISO 11783 Communication and D-GNSS Position Data," the authors present an algorithm developed to handle georeferenced data recorded during plowing operations, automating the calculation of various area-related parameters. Data were recorded using a data logger (GL2000 CAN-Bus, Vector Informatik GmbH, Stuttgart, Germany) connected to the diagnostic interface of the tractor employed for the task. The recorded data included wheel-based machine speed, differential GNSS (D-GNSS) coordinates, and timestamps. MATLAB R2016b software (The MathWorks Inc., Natick, MA, USA) was utilized to analyze this data using various filtering equations to identify passes and subsequently compute parameters such as cultivated area, boundaries, and overlaps among the cultivated tracks.

The algorithm successfully detected 58 passes, corresponding to the number of lifting and lowering points, demonstrating the algorithm's functionality. Moreover, various common indicators were computed for overlap analysis, the cultivated area was quantified, and field boundaries were identified, affirming the validity of the results. The authors recommend the use of this algorithm for applications such as documenting and invoicing agricultural tasks, with overlapping analysis serving as an indicator of operational efficiency.

2.4.2 Digital Transformation of Food Systems;

Ensuring food security is a crucial factor in advancing overall human well-being and human security [25]. The review article authored by Raheem et al. [26], titled "Digital Transformation of Food Systems to Enhance Food and Nutrition Security in the Barents Region," delves into the Barents region, where traditional foods like potatoes, meat, fish, berries, and a diverse range of dairy products are processed primarily by small and medium enterprises to enhance preservation and distribution. Digitalization has the potential to augment the value of traditional foods by optimizing harvesting processes, increasing production, reducing waste, and improving storage and distribution mechanisms.

For instance, the integration of sensors and data processing applications within food system digitalization is expected to enhance the predictive accuracy of food value chains in the Barents region. The primary objectives of this review article were to identify challenges, enhance sustainability, and promote food system digitalization. The article is structured into seven sections, commencing with an introduction, followed by an exploration of the current conditions in the Barents region concerning climate change, human activities, and food system digitalization up to section 3. From Section 4 onwards, the authors delve into the role and impact of various digital technologies within food system components and sustainability, concluding with future implications for the Barents region.

This comprehensive review serves as a valuable resource for conceptualizing a framework for food system digitalization, offering insights that can inform policymakers and stakeholders in the study region, ultimately supporting food security efforts.

2.5 Sunflower Seed Post-Harvest Processing;

Drying sunflower seeds is a common requirement for safe storage, as excessive moisture levels can result in dry matter loss and promote microbial activity. The article authored by Munder et al. [27], titled "Enhancing Standard Models for High Oleic Sunflower Seed Drying through Continuous Measurements in Dynamic Systems with Embedded Devices," explores innovative methods for determining sorption and drying data at typical handling temperatures for agricultural products. The primary objective was to develop a robust drying model specifically for high oleic sunflower seeds, based on data obtained from sorption and drying experiments.

Laboratory experiments were conducted to collect a comprehensive dataset of equilibrium moisture content through a gravimetric analyzer and to gather single-layer drying kinetics data under various drying conditions. These collected data served as the foundation for constructing a generalized single-layer drying model that considers air conditions. The embedded systems utilized in this study facilitated the recording of a substantial amount of experimental data, which were employed to fit semi-empirical and analytical sorption and drying models.

The results demonstrated that equilibrium moisture content increased at elevated water activity levels, as observed in the sorption experiments. This study presents an appropriate model for high oleic sunflower seeds, offering insights into the drying process across a broad spectrum of humidity and temperature conditions.

3. Conclusions;

This special issue encompasses a diverse array of sensor applications in agriculture, showcasing recent research findings in this field. Authors have made valuable contributions spanning soil and plant sensing, farm management, and post-harvest applications. The articles featured in this special issue are regarded as valuable additions to the scientific community, with the editors anticipating that they will inspire additional ideas and novel applications for sensors within the realm of agriculture.

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