Drone-Based Sensing and Imaging for Fruit Crop Monitoring: A Review

Abstract

The global fruit production industry suffers from numerous problems in the yield, quality, and food safety context. Monitoring fruit crops helps identify areas of improvement and makes decisions based on data. Monitoring fruit crops through drones allows for the real-time imaging and sensing of crop health, growth, and development at a very high resolution. Different types of sensors that are utilized in monitoring are RGB, multispectral, hyperspectral, thermal, and LiDAR. Applications include yield estimation and prediction, crop growth monitoring, disease detection and diagnosis, pest detection and management, and nutrient deficiency detection and water stress monitoring. Case studies demonstrate the application and efficiency of drone-based sensing and imaging in fruit crop monitoring. Despite these potential drawbacks such as weather conditions, the sensor calibration, and complexity related to processing data, the technology certainly is able to revolutionize the fruit production business. Future directions include integration with other technologies, development of specialized sensors and cameras, and applications. Standardization and best practices are crucial for mass adoption. In general, drone-based sensing and imaging is a promising solution to fruit crop monitoring, as it will be able to provide precision agriculture practices that reduce waste and promote sustainability in agriculture.

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1.Introduction

The global fruit production industry has faced various challenges in terms of optimum yield, quality, and food safety. Fruit crop monitoring is an important task for identifying possible issues, making data-driven decisions, and implementing precision agriculture practices (Zhang et al., 2020). Precise monitoring will allow farmers to detect the early signs of stress, disease, and pests and reduce yield losses and environmental impact (Gomez et al., 2019). Timely monitoring allows farmers to detect potential problems, make data-driven decisions, and apply precision agriculture practices. Fruit production around the world faces several challenges in ensuring optimum yield, quality, and food safety.

Fruit crop monitoring plays an essential role in pointing out possible issues, data-based decisions, and precision agriculture practice implementation by Zhang et al. (2020).

Correct monitoring gives a farmer a chance to discover the earliest signs of stress, diseases, or pests that eventually cause lesser losses and also lesser impact on the environment, as identified by Gomez et al. (2019). Timely monitoring enables farmers to pinpoint potential problems, make data-driven decisions, and employ precision agriculture.

Traditional methods for fruit crop monitoring rely highly on manual inspection, ground-based sensors, and satellite images. These traditional methods are very limited as they entail; Labor and time consumption for data collection (Rasmussen et al., 2018), lower spatial coverage and resolution (Matese et al., 2015), erroneous or late decision making (Candiago et al., 2015), and higher costs that relate to the manual inspections and satellite images (Lottes et al., 2017). Moreover, traditional methods lack real-time insight, which delays swift action.

Recent advances in drone technology have revolutionized the agricultural environment. Unmanned Aerial Vehicles (UAVs) equipped with sophisticated sensors and cameras provide high-resolution, real-time data on crop health, growth, and development (Toth et al., 2019). Drone-based sensing and imaging have emerged as valuable tools for precision agriculture, overcoming traditional monitoring limitations (Sankaran et al., 2015). Drone-based sensing and imaging have emerged as valuable tools for precision agriculture, overcoming traditional monitoring limitations. The integration of drone technology with precision agriculture enables efficient monitoring of large areas, reducing labor costs and enhancing decision-making (Lottes et al., 2017). Drones with various sensors and cameras capture valuable data concerning crop health, growth, and development.This review is comprehensive of drone-based sensing and imaging for monitoring fruit crops based on principles, technologies, applications, advantages, challenges, and future direction. The aim of this review is to synthesize existing research on the effectiveness of drone-based sensing and imaging in fruit crop monitoring.

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2. Drone Platforms and Sensors

Drone platforms are very significant for fruit crop monitoring, as they offer numerous types according to specific applications (Zhang et al., 2020). Fixed-wing drones look like typical planes and are useful for large crops due to their endurance and high-flying speed (Toth et al., 2019). Rotary-wing drones, like quadcopters, are more agile and can hover, making them ideal for smaller, complex orchard environments (Sankaran et al., 2015). Hybrid drones have a fixed-wing and rotary-wing combination, providing versatility. Sensor selection is vital for successful fruit crop monitoring.

RGB cameras are utilized for high-resolution photography (Candiago et al., 2015), whereas multispectral cameras capture reflectance data over specific wavelengths (Matese et al., 2015). Hyperspectral cameras offer detailed spectral information, and this can be used for the detection of minor changes in crop health (Gomez et al., 2019). Thermal cameras are used to detect temperature variations that can indicate the presence of water stress or illness (Lottes et al., 2017). LiDAR sensors offer high-resolution 3D models of orchards, enabling crop height and density analysis (Rasmussen et al., 2018).

The quality of data, in great measure, is affected by camera systems and configurations. The use of single-camera setups is appropriate for simple monitoring tasks, while multi-camera configurations allow for the simultaneous capture of data from multiple angles (Toth et al., 2019). Stereo camera systems offer 3D imaging capabilities, improving spatial awareness (Zhang et al., 2020); some drones integrate multiple sensor types, allowing for comprehensive data collection; efficient sensor-drone integration ensures smooth data collection and processing; this integration includes sensor calibration, synchronization, and data fusion techniques (Sankaran et al., 2015); advanced drone platforms frequently have modular designs that make it simple to swap out or upgrade sensors; integration also takes communication protocols, power management, and data storage into consideration.

The choice of drone platform and the sensor suite mainly depends on monitoring objectives, orchard features, and environmental conditions (Gomez et al., 2019). For example, to detect fruit and count the number, RGB imaging at a high resolution might be acceptable, while for disease diagnosis or analysis of nutrient deficiency, one may need multispectral or hyperspectral imaging.

3. Applications in Fruit Crop Monitoring

Drone-based sensing and imaging have numerous applications in fruit crop monitoring, enhancing the efficiency and accuracy of agricultural practices.

3.1. Yield Estimation and Prediction, Crop Growth Monitoring:

Drones mounted with RGB, multispectral, and hyperspectral cameras provide accurate yield estimation and forecast (Gomez et al., 2019). Crop growth, height, density, and vigor can be monitored by assessing vegetation indicators such as NDVI and EVI (Matese et al., 2015). This information allows for more informed judgments on pruning, thinning, and

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harvesting. Additionally, drone-based 3D model using LiDAR and photogrammetry permits the accurate assessment of crop height and density (Rasmussen et al., 2018).

3.2. Disease Detection and Diagnosis, Pest Detection and Management

Drones are useful in detecting fungal, bacterial, and viral diseases such as powdery mildew and citrus canker (Candiago et al., 2015). Hyperspectral imaging identifies subtle changes in spectral reflectance, indicating disease presence (Gomez et al., 2019). In the same way, thermal cameras installed in drones detect temperature variations, which help in pest management (Lottes et al., 2017). For example, thermal imaging detects areas with increased insect activity, allowing for targeted pesticide application.

Drones detect fungal, bacterial, and viral diseases like powdery mildew and citrus canker (Candiago et al. 2015). Hyperspectral imaging detects even slight variations in spectral reflection, indicating the presence of illness (Gomez et al., 2019). Conversely, a drone with a thermal camera will detect temperature differentials and aid in the management of pests (Lottes et al., 2017). For instance, thermal imaging shows areas of high activity of insects so that targeted pesticide application can be provided.

3.3. Nutrient Deficiency Detection and Water Stress Monitoring:

They sense nutrient deficiencies such as those of nitrogen and potassium levels (Toth et al., 2019). A drone-based thermal imaging assesses water stress, focusing on areas needing adjustments of irrigation (Zhang et al., 2020). This is helpful to precisely schedule irrigation without waste but with optimal growth of the crops. Such applications ensure adoption of precision agriculture, increased productivity of crops, reduced application of chemicals, and practicing sustainable agriculture.

Multispectral and hyperspectral imaging can detect nutrient shortages such as nitrogen and potassium (Toth et al., 2019). Drone-based thermal imaging measures water stress and identifies regions that require irrigation changes (Zhang et al., 2020). This enables more efficient irrigation scheduling, avoiding water waste and maintaining maximum crop growth. Growers can embrace precision agriculture practices by combining these applications, which increase crop output, reduce pesticide use, and promote sustainable agriculture.

4. Image Processing and Analysis Techniques

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Effective image processing and analysis are important to extract valuable information essential for useful information derivation from drone-acquired images in fruit crop monitoring. This section discusses various techniques employed in image examines the many approaches used in picture processing and analysis.

Image preprocessing is an important pre-processing step for preparing images ready for analysis. Registration is an essential step in getting images in a position to be analysed. Registration is the process of aligning multiple images taken several pictures collected at different times or angles to form a single, holistic image (Gonzalez et al., 2017). Filtering methods like Gaussian or median filtering reduce noise and enhance image quality while enhancing image quality (Jensen et al., 2017). Normalization helps maintain consistency in intensity and contrast of images so that one can compare across images (Liu et al., 2018). Fruit crop monitoring employs OBIA very extensively.

OBIA involves segmenting images into meaningful objects, such as individual trees or fruit, and extracting relevant features (Blaschke et al., 2014). This approach enables precise analysis of crop health, growth, and development. OBIA can easily identify the alterations in the size, shape, and color of tree canopies, thereby indicating stress or presence of disease (Moser et al., 2016). The implementation of machine learning-based methods for image analysis to monitor fruit crops is now progressively increasing every day. For instance, some of the classifying algorithms that can ensure precise recognition of crop type, growth phases, as well as the existence of diseases include support vector machines (SVM) and random forests (Mulla et al., 2017).

Continuous factors like fruit quality and yield are predicted by regression methods (Gomez et al., 2019). Large datasets are necessary for the training and validation of these algorithms. In fruit crop monitoring, image analysis has been transformed by deep learning approaches. According to Kamilaris et. al. (2018), CNN shows great effectiveness in picture categorization as well as object recognition tasks. LSTM networks and RNN check spatial and temporal patterns in image sequences (Xu et al., 2020).

These methods enable one to automatically detect minute changes in crop development as well as health. Data integration and fusion combine information from sources like drone-acquired images, weather data, and soil sensors. This integrated approach allows one to have a comprehensive insight into crop growth, development, and response to environmental factors (Zhang et al., 2020). Techniques in data fusion, such as PCA and ICA, reduce the dimensionality of data and enhance efficiency in analysis (Liu et al., 2018).

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5. Case studies and examples

5.1 Apple Yield Estimation using Drone-Based RGB Imaging

A study conducted in Washington State, USA, drone-based RGB imaging was utilized to estimate apple yield (Gomez et al., 2019). The researchers employed object-based image analysis (OBIA) to segment images into individual trees and extract features related to yield. Results showed a strong correlation between drone-estimated yield and actual yield (R2 = 0.85). This study demonstrated the potential of drone-based RGB imaging for accurate yield estimation in apple orchards.

5.2. Citrus Disease Detection Using Multispectral Imaging

Candiago et al. (2015) employed multispectral imaging to identify Huanglongbing or citrus greening disease caused by a bacteria *Candidatus liberibacter*. Images were captured by using a camera mounted on the drone and machine learning classification was performed for distinguishing healthy from diseased trees. With 92% accuracy of detection, the results have been demonstrated for the efficacy of early detection of diseases using multispectral imaging in citrus orchards.

1.3. Grapevine Water Stress Monitoring using Thermal Imaging

A study in Italy used thermal imaging to track water stress in grapevines (Matese et al., 2015). Thermal images taken by drones were analyzed to detect temperature changes that could be indicative of water stress. The results indicated a high correlation between the thermal indices and the levels of water stress (R2 = 0.90). This study proved the potential of thermal imaging in precision irrigation management in grapevine cultivation.

5.4. Mango Fruit Detection and Counting with LIDAR

Scientists in Australia used LIDAR (Light Detection and Ranging) to detect and count mango fruit (Turner et al., 2019). LIDAR point clouds were analysed to identify fruit and estimate yield. The results indicated an accuracy of 95% in fruit detection and counting. The study proved the efficiency of LIDAR for yield estimation in mango orchards.

6. Challenges and Limitations

Although drone-based sensing and imaging of fruit crops holds much promise, there are still various challenges and limitations.

6.1. Weather Conditions

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Weather conditions significantly impact drone operations and data quality. Wind, rain, and extreme temperatures can compromise drone stability, sensor accuracy, and image quality (Toth et al., 2019). Sunlight variability also affects image quality, with harsh sunlight causing saturation and shadows (Gomez et al., 2019). Researchers have proposed strategies to mitigate weather-related issues, such as using weather-resistant drones and adjusting flight schedules (Zhang et al., 2020).

6.2. Sensor Calibration and Validation

Sensor calibration and validation are important to ensure proper data collection. However, sensor drift, noise, and variability can degrade the quality of data collected (Matese et al., 2015). Calibration processes are tedious and need specialized equipment (Candiago et al., 2015). Validation methods such as ground-truthing are very important to validate the accuracy of sensors (Turner et al., 2019).

6.3. Data Processing and Analysis Complexity

Data processing and analysis are an essential part of drone-based sensing and imaging. However, there exist challenges in processing vast data sets, noise handling and errors, and extracting meaningful information from this data (Liu et al., 2018). Advanced algorithms and machine learning techniques can help with overcoming these challenges but necessitate heavy computational resources and skillset knowledge (Kamilaris et al., 2018).

6.4. Regulatory Frameworks and Privacy Concerns

Regulatory frameworks that govern the use of drones vary globally, thus causing uncertainty and liabilities for users (European Union Aviation Safety Agency, 2020). Data collection and storage, therefore, pose privacy issues that need to be taken into consideration (Federal Aviation Administration, 2020). The researcher must adhere to the regulation and privacy concerns by having transparent data handling practices.

6.5. Cost-Effectiveness and Scalability

Cost-effectiveness and scalability are essential for large-scale adoption. Drone-based sensing and imaging can be costly, especially when high-resolution sensors and complex analytics are used (Lottes et al., 2017). Scalability becomes a problem when drone-based solutions are applied to large agricultural operations (Gomez et al., 2019). Some researchers are working on finding cost-effective alternatives, such as using low-cost sensors and exploiting existing infrastructure.

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7. Future Directions

The development of drone-based sensing and imaging has many future directions that have the potential to enhance fruit crop monitoring.

7.1. Integration with Other Technologies

Integration with emerging technologies such as Internet of Things (IoT), robotics, and Artificial Intelligence (AI) will transform fruit crop monitoring (Kamilaris et al., 2018). IoT sensors can provide real-time soil moisture and temperature data, while robotics can automate pruning and harvesting tasks (Liu et al., 2020). AI-powered analytics can optimize data analysis, predictive modeling, and decision-making (Gomez et al., 2019).

7.2. Development of Specialized Sensors and Cameras

Sensor and camera technology have the potential and can offer improved data quality and resolution. Specific sensors for targeted stresses, diseases, or nutrient deficiencies will enhance monitoring accuracies (Matese et al., 2015). High-resolution cameras with new spectral ranges (hyperspectral, multispectral) provide insights into crop health and growth (Candiago et al., 2015).

7.3 Better Data Analysis and Decision Support Systems

Next-generation data analysis and decision support systems will be able to make more informed decisions. Advanced machine learning algorithms will improve predictive modeling, anomaly detection, and recommendation systems (Kamilaris et al., 2018). Cloud-based platforms will allow for data sharing, collaboration, and integration with other agricultural systems (Liu et al., 2020).

7.4. Expanded Applications

Drone-based sensing and imaging will extend beyond crop monitoring to precision irrigation, fertilization, and pest management. Precision irrigation systems will apply water according to soil moisture and crop water stress (Zhang et al., 2020). Drone-based fertilization will allow targeted nutrient application, minimizing waste and environmental impact (Gomez et al., 2019).

7.5. Standardization and Best Practices

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Standardization and best practices can only be achieved through this wide-scale adoption. Standardization of protocols in drone operation, data collection, and analysis will ensure consistency and allow comparability among studies (Toth et al., 2019). Best practices development for data management, storage, and sharing will boost collaboration and innovation (Federal Aviation Administration, 2020).

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