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Integration of Smart Drones and AI into Agriculture – A Review

Abstract

New technological trends like smart drones and Artificial Intelligence (AI) have significant potential in transforming the agriculture industry. With the growing demands of the ever-increasing population, the global need for food supplies continues to rise. Efficiently handling food production is crucial for the growing population, thus employing the new technologies into the farming sector will help in producing crops with high output while minimizing the resources used. This paper explores the integration of AI and smart drones in agriculture, emphasizing precision farming and sustainable practices. By employing advanced sensors and AI-driven analytics, smart drones facilitate detailed crop monitoring, optimal irrigation management, early yield estimation, and make onerous and time-consuming data collections simpler and more efficient. These technologies enable precise resource application by reducing waste and environmental impact while enhancing productivity and efficiency. Furthermore, AI algorithms analyze historical and real-time data to improve yield predictions and farm management strategies. The fusion of AI and Smart drone technology in agriculture not only increases operational efficiency but also contributes to more sustainable farming and better resource conservation. However, challenges such as high implementation costs, the need for skillsets to understand data and operate drones, certification requirements, and restricted airspace issues need consideration to make sure the technology is adopted effectively and seamlessly.

Introduction

Technology has always been at the forefront of agricultural transformations, from machines operating with fuel to autonomous vehicles that navigate in the field to accomplish cumbersome tasks with minimum to no human intervention. One of the major innovations in agriculture is drones powered by Artificial Intelligence (AI). Today, drones with AI systems are transforming the core methods by which farmers engage with agricultural fields. Drones can efficiently and accurately perform complex and labor-intensive tasks that typically require human capabilities, such as monitoring crop growth, detecting diseases, and precision spraying (Dutta and Goswami, 2020; Raouhi et al. 2023). Drones are not mere tools for capturing aerial imagery but a jumpstart for precision agriculture, with answers to reduce human labor while increasing productivity and sustainability at the same time (Dutta and Goswami, 2020; Kumar and Sriram, 2024). With labor shortages, climate change, and increasing food demand looming over global agriculture, AI-powered drones are turning pivotal in the development of smart, efficient, and environmentally sustainable farming (Raouhi et al., 2023; Wakchaure et al., 2023). These AI-powered drones are equipped with high-resolution sensors and cameras. These drones capture large amounts of data, which AI algorithms process to analyze various aspects of crop health, soil conditions, and field productivity. For example, machine learning algorithms can identify crop diseases by analyzing image patterns, while deep learning algorithms are used to detect changes in vegetation to optimize irrigation schedules (Shahi et al., 2022; Wakchaure et al., 2023).

These AI-powered drones are autonomously flown across the field to collect vast amounts of data related to crop, soil and field. These drones can communicate with a remote drone center, which can then be further used to analyze the data and extract useful information to help users in smart decision-making about the field to maximize the yield with minimum resources used (Raouhi et al., 2023). These advanced sensors and AI-powered drones have brought a revolution in conventional farming practices by offering unprecedented accuracy and efficiency. For example, the use of drones in modern agriculture, from precision spraying to crop monitoring, soil moisture estimation, irrigation management, yield estimation, and canopy measurements (Kumar and Sriram, 2024).

Precision spraying is one of the key applications of drones that ensures fertilizers, pesticides, and herbicides are applied only where they are needed, thus reducing waste and reducing the impact of chemicals on the environment (Javaid et al., 2023; Shahi et al., 2022). Through monitoring, drones equipped with multispectral, hyperspectral, and other advanced sensors can provide real-time information on plant health and detect problems, such as disease, pest infestation, or nutrient deficiencies at an early stage so that the farmers can intervene before major damage has been done (Kumar and Sriram, 2024; Oikonomidis et al., 2022; Wang et al., 2023).

Other key areas where drones are making a difference include soil moisture estimation and irrigation management (Javaid et al., 2023). By capturing aerial drone imagery and analyzing it with advanced AI-based models and algorithms, drones can enable farmers to come up with information about the amount of moisture in the soil and helps farmers in irrigating the field only where and when it is necessary, this enables precision water management (Ge et al., 2019; Javaid et al., 2023; Kumar et al., 2022a; Olson and Anderson, 2021). This becomes an important aspect, especially in places with little or no water, since precise irrigation is necessary to maximize crop yield while saving resources at the same time (Kumar et al., 2022b, 2023, 2024).

Yield estimation using drone surveillance is a data-driven prediction of harvest outcomes. Drones can analyze crop growth and canopy density for accurate forecasts, enabling farmers to plan logistics and market strategies more effectively (Nhamo et al., 2020; Olson and Anderson, 2021; Raouhi et al., 2023). Canopy estimation using drone imagery depicts the extent of crop coverage and growth pattern to the farmer, thus helping in field management and making smart decisions related to the crop (Valluvan et al., 2023). From being the essential transformers of various aspects of farming, drones are also improving productivity levels while also pushing environmentally sustainable agricultural practices. When drones are embedded with advanced sensors, they are termed as smart drones, which improves the efficacy of resource management and improves crop production with intelligent and smart decision-making based on AI powered data analytics. In this paper, we review the integration of drones with AI and how it is transforming modern agricultural practices.

Smart Drones

In general, drones are flying machines, but smart drones are something more than just flying machines. For example, imagine a bird's-eye view of the farm, but with eyes that can see beyond what a human can, this is achieved using smart drones. Smart drones are drones equipped with multiple high-tech sensors that can collect a lot of information about the field and use it to perform advanced analysis using AI (Raouhi et al., 2023; Shahi et al., 2022). The most important sensors are the cameras, especially multispectral and hyperspectral cameras, and LiDAR. These drones can capture images in multiple wavelengths of light, both visible and invisible. This technology allows farmers to see the health of crops throughout the field in a way never before possible, identifying issues like disease, water stress, and nutrient stress before they become visible to the human eye (Qu et al., 2024). These drones can process data in real-time or store it for later analysis. With the help of AI driven software intelligence, smart drones can collect, process, and analyze images and sensor data to provide valuable insights. Smart decisions can be devised to ensure the best possible yield of crops with minimal resources used (Raouhi et al., 2023; Singh et al., 2024). Smart drones also incorporate advanced navigational technologies that enable precision farming. These drones leverage RTK (Real-Time Kinematic) GPS, enabling centimeter-level accuracy compared to the typical meter-level precision of standard GPS. While RTK technology is not new to agriculture and has been widely used in tractors and ground equipment for years, its integration into drones represents a significant advancement. Unlike ground-based systems, drones equipped with RTK GPS can provide an aerial perspective, covering large areas quickly and offering a complementary approach to traditional methods This high level of precision allows monitoring row crops with specific spacing, creating detailed maps highlighting variations in field conditions such as soil moisture and soil fertility for targeted interventions (Javaid et al., 2023).

Moreover, the data collected by smart drones is invaluable for long-term agricultural planning. Using Normalized Difference Vegetation Index (NDVI) we can compare the crop conditions at various growth stages during the growing season. Not all drones have precision in predicting crop yields or other crop phenotypes, which can be a limitation; however, selecting a specific sensor or camera for the objective can provide accuracy in yield estimation with the help of AI-based models. By analyzing trends over time, farmers can make informed decisions about crop rotation, planting schedules, and resource allocation. Predictive analytics can forecast potential problems before they occur, such as pest invasions or adverse weather conditions, enabling preemptive actions that can save crops and resources (Chergui and Kechadi, 2022). In essence, smart drones represent a convergence of agriculture and technology, transforming farming into a high-tech industry driven by data and efficiency. This technological revolution not only increases the sustainability of farming practices but also boosts productivity and profitability in an era of increasing environmental and economic challenges (Raouhi et al. 2023).

Artificial Intelligence

Artificial Intelligence (AI) is about enabling computers to process information, learn from data, and make decisions. AI learns patterns in the data, and experiences through extensive training and optimization techniques (Wakchaure et al., 2023). Now AI is being used in almost every field of research, touching almost every aspect of life. In agriculture, AI can process vast amounts of information far beyond our capability, providing insights and recommendations that help farmers make better decisions like optimizing irrigation schedules to conserve water and improve crop yield (Wakchaure et al., 2023).

Smart Drones and AI Applications in Agriculture

Precision spraying

Precision spraying is at the peak of agricultural innovation, and smart drones are playing a very important role in it. By analyzing the data collected on soil composition, moisture levels, and crop health, drones empower the farmers with the knowledge to tailor their practices to the exact needs of their fields (Dutta and Goswami, 2020; Shahi et al., 2022). This means that water, fertilizers, and pesticides are no longer applied uniformly across the entire fields but are instead distributed with pinpoint accuracy where they are needed (Dutta and Goswami, 2020; Javaid et al., 2023; Shahi et al., 2022), also known as targeted spraying. Smart drones with spraying capabilities can autonomously navigate through the field and apply pesticides at different targeted locations and rates using variable spray parameters (Figure 1). It can also collect drone imagery data simultaneously, which is further used to analyze and extract useful information of the field. This also helps provide information about the crop where the spraying application is necessary. Such applications result in a significant reduction in input costs and minimize the environmental impact. This kind of intelligent approach not only enhances crop productivity but also increases sustainability in farming (Dutta and Goswami, 2020).

Figure 1: Smart drone performing precision spraying (photo by Abubakar Palli).

Crop monitoring and management

Drones can fly over large areas, capturing detailed images that help farmers understand the crop conditions in less time compared to manual crop monitoring (Figure 2). This level of detail allows for the early detection of issues that could potentially harm yields, such as fungal infestations, insect attacks, and water and nutrient deficiencies.

Figure 2: Drone monitoring the crop with multispectral sensors and performing data collection (photo by Abubakar Palli)

The key advantage here is the early action taken by identifying problems before they escalate. Farmers can take specific targeted measures to mitigate issues early, thereby safeguarding their crops (Dutta and Goswami, 2020). This proactive approach to crop management not only ensures crop health but also conserves labor and resources by eliminating the need for broad-spectrum solutions. Furthermore, the high-resolution imagery provided by drones enables farmers to create detailed maps of their fields, highlighting variations in crop health, soil moisture, and nutrient levels (Kumar et al., 2022; Oikonomidis et al., 2022). This precision mapping allows for the implementation of variable-rate applications of fertilizers, pesticides, and water, optimizing resource use and reducing environmental impact (Wang et al., 2023). The real-time data collected by drones also facilitate better management decisions throughout the growing season. Farmers can track crop development stages, estimate yields more accurately, and determine optimal harvest times (Wang et al., 2023). This level of insight helps in planning labor allocation, scheduling equipment, and managing storage facilities more efficiently. Additionally, drone technology integrates well with other smart farming practices, such as IoT sensors and AI-powered analytics, creating a comprehensive farm management system that enhances overall productivity (Kumar and Sriram, 2024).

As drone technology continues to advance, new applications are emerging. For instance, agricultural drones are now equipped with multispectral, hyperspectral, LiDAR, and thermal sensors that can detect subtle changes in plant physiology invisible to the naked eye (Qu et al., 2024; Raouhi et al., 2023; Shahi et al., 2022; Singh et al., 2024;). Drones equipped with these cameras can take images of the field in various spectrums other than visible RGB. This extra data is used to process and extract crop information such as crop water stress or nutrient stress etc. using vegetation indices such as normalized difference vegetation index (NDVI) (Figure 3). NDVI is a measure used to assess vegetation health by comparing the difference between near-infrared which vegetation strongly reflects, and red light which vegetation absorbs. It provides insights into the spatial variation in the crop conditions at the time of data collections, which can help to determine the issues in different parts of the field. This information is also used in extracting details about where in the field the resources should be allocated for maximum output (Qu et al., 2024; Wang et al., 2023).

Figure 3. NDVI processed with drone imagery collected using multispectral sensor.

Irrigation management

Smart drones are equipped with advanced sensors that play a pivotal role in optimizing irrigation practices. By assessing soil moisture levels across different parts of a field, drones can identify the areas that are dry and in need of water, as well as the areas where water is abundant (Olson and Anderson, 2021). Aerial imagery can be used to create the management zones to support the in situ measurements during the growing season. This information is crucial for creating efficient irrigation schedules that ensure crops receive the right amount of water at the right time at the right place. Such precision in irrigation management not only conserves water but also prevents problems related to over-or under-irrigation that affects the crop quality (Kumar et al., 2023). Data collected using drones can provide soil moisture status across the field. The real-time soil moisture status in the field can help with irrigation schedules, with direct communication to irrigation systems equipped with AI. This automated, feedback-driven approach allows for precision water management, adapting to changes in weather conditions that affect soil moisture levels, such as unexpected rainfall or drought (Ge et al., 2019; Olson and Anderson, 2021).

The benefits of using drones for irrigation management extend to economic advantages as well. By optimizing water usage, farmers can reduce the cost associated with water consumption, which is particularly crucial in arid or semi-arid regions where water is scarce and expensive (Nhamo et al., 2020). This is also true in the humid to subtropical regions due to unexpected rainfall variations or lack of rainfall within the growing seasons (Kumar et al., 2022). Furthermore, healthier crops that receive optimal water amounts are likely to yield higher quality produce (Kumar et al., 2022), which can command better prices in the market, enhancing the overall profitability for farmers.

Yield estimation

Estimating yield is a critical aspect of farm management, affecting everything from revenue projections to supply chain logistics. Smart drones contribute to this process through their ability to collect and analyze data on crop density, health, and maturity. By providing accurate, up-to-date estimates of potential yield, drones help farmers make informed decisions about resource allocation, harvest timing, and market strategies (Dutta and Goswami, 2020; Javaid et al., 2023; Nhamo et al., 2020; Olson and Anderson, 2021; Raouhi et al., 2023; Shahi et al., 2022; Wakchaure et al., 2023;). This foresight can lead to better planning, reduced waste, and optimized profits. Moreover, data collected over time can offer insights into the effectiveness of different farming practices, guiding future decisions for improved productivity. In addition to helping with immediate crop management decisions, the data gathered by smart drones also supports long-term agricultural strategies. Trends derived from season-over-season yield data can reveal the impact of different irrigation strategies, crop rotations, soil amendments, and pest management practices on overall productivity. Such insights are invaluable for fine-tuning agronomic techniques to boost future yields and sustainability (Chergui and Kechadi, 2022; Olson and Anderson, 2021; Wakchaure et al., 2023).

The integration of drone data with other digital farming tools, such as satellite imagery and IoT sensors, creates a comprehensive decision-making framework. This interconnected system not only enhances the accuracy of yield predictions but also facilitates a holistic approach to farm management that is responsive to both environmental sustainability and market demands (Javaid et al., 2023; Chergui and Kechadi, 2022). This comprehensive data integration is paving the way for a new era of precision agriculture, where decisions are driven by data, leading to more resilient agricultural practices and sustainable food systems.

Canopy estimation

Canopy estimation plays a crucial role in understanding crop health, growth patterns, and overall farm management. Traditionally, farmers had to rely on ground-level measurements or rough visual assessments, which were time-consuming, labor-intensive, and often inaccurate. However, with smart drone technology, canopy estimation has taken a leap forward, offering farmers a more accurate, efficient, and cost-effective solution (Šiljeg et al., 2023; Valluvan et al., 2023). With their ability to carry high-resolution cameras and sensors, smart drones have the potential to do detailed aerial imaging in crop canopies, while large areas are covered quickly and efficiently (Ge et al., 2019; Raouhi et al., 2023). Images captured from such cameras are further processed for measurements such as leaf area index and density to provide an accurate picture of the growth and overall condition of the crop. Drones equipped with various light sensors, including infrared and near-infrared, can detect subtle signs of plant stress, such as water stress or nutrient deficiencies. These issues are often difficult or nearly impossible to identify through manual inspection and drones can do this precisely. (Qu et al., 2024). Finally, base canopy estimation through drones enables farmers to make smart decisions for the healthy growth of crops and more efficient management of the farm.

Benefits of AI in Agriculture

The integration of AI and drones in agriculture represents a pivotal shift towards more sustainable and productive farming practices. By harnessing these technologies, farmers can achieve unprecedented levels of efficiency and productivity, while also conserving resources and protecting the environment. As AI and drone technologies continue to evolve, their potential to transform agriculture and support global food security becomes increasingly clear.

Increased Efficiency and Productivity

One of the impacts of integrating AI and drones in agriculture is the increase in efficiency and productivity. Drones, equipped with AI-systems and sensors, can cover large areas of farmland in a fraction of the time than it would take using traditional methods (Shahi et al., 2024; Singh et al., 2024). The rapid data collection and processing capability allows for quick identification of issues that may affect crop health, such as pest infestations or water and nutrient deficiencies. AI-based models can then analyze this data to provide useful insights, enabling farmers to address problems promptly and effectively (Javaid et al., 2023). Furthermore, AI-powered systems can automate repetitive tasks such as planting, irrigation, and harvesting. This not only reduces the workload on farmers but also minimizes human error, leading to more consistent and reliable agricultural outputs (Shahi et al., Wakchaure et al., 2023). By optimizing these processes, AI and drones help farms operate more efficiently.

Resource Conservation and Environmental Benefits

Agriculture is a resource-intensive endeavor, requiring substantial amounts of water, fertilizers, and pesticides. However, the over- and under-application of these inputs can lead to environmental degradation, including soil depletion, water pollution, and loss of biodiversity. Additionally, over or under application can result in significant economic costs to farmers, such as wasted inputs, reduced crop yields, or increased expenses for corrective measures. Precision agriculture addresses these challenges through variable rate technologies like smart sprayers, advanced rate controls, and precision soil maps, allowing farmers to tailor applications to site-specific needs across their fields. AI and drone technologies offer a new approach to these existing practices. Drones, in supplement to these existing technologies, enable more flexible, real-time monitoring, and localized treatment, particularly in areas where ground-based equipment may be limited, this further enhances the precision and sustainability of agriculture (Shahi et al., 2022). By gathering precise data on soil moisture levels, crop health, and environmental conditions, drones enable farmers to adopt site-specific best agricultural management practices. This targeted approach reduces the overall consumption of water, fertilizers, and pesticides, minimizing waste and environmental impact. Moreover, AI-driven analytics can help in selecting the most suitable farming practices for a given set of environmental conditions, further enhancing the sustainability of agricultural operations (Friha et al., 2021).

Improved Crop Health and Yield Predictions

Accurate prediction of crop yields is vital for effective farm management and market planning. AI and drones play a crucial role in improving these predictions by providing detailed insights into crop health and development. Drones capture high-resolution images of crops across the field at different growth stages, which AI systems analyze to detect signs of stress, disease, or other crop variabilities. This frequent monitoring enables early detection of the problems to improve overall crop health (Wakchaure et al., 2023; Wang et al., 2023). Additionally, AI algorithms can process historical data alongside current observations to forecast future yields with high accuracy. These predictions allow farmers to make informed decisions about harvest timings, resource allocation, and market sales, reducing the risk of crop yield loss. Enhanced yield predictions not only improve the economic outcomes for farmers but also contribute to the stability of food supply chains.

Future Scope

With all the technological trends happening in other sectors, it doesn’t take much time for these new age technologies to be adapted into the agricultural sector. AI technologies and smart drones are transforming farming practices. With the addition of

IoT sensors, autonomous robots, and other agricultural technologies, the efficiency and accuracy of the farming sector can be greatly improved (Dayioğlu and Türker, 2021). As AI and machine learning models become more sophisticated, drones can provide deeper insights into crop health, soil conditions, and resource usage. These developments will allow for more precise, data-driven decision-making, reducing waste and enhancing productivity (Friha et al., 2021).

Farms may become increasingly automated with autonomous drones coordinating with advanced technologies. These drones and robots can constantly monitor the field with the help of advanced IoT sensors and can analyze the data with new AI models, extracting new insights that could help increase productivity (Dayioğlu and Türker, 2021). Ultimately the farming sector can witness tremendous growth in the near future.

Conclusions

The integration of AI and smart drones into the farming industry is transforming agricultural management practices. Drones equipped with advanced sensors and AI-driven analytics are changing how farmers manage their crops and resources, making processes like precision spraying, crop monitoring, irrigation management, and yield estimation more efficient and accurate. These innovations not only help reduce costs and labor but also minimize negative environmental impacts by ensuring resources such as water, fertilizers, and pesticides are used precisely where and when they are needed.

One of the advantages of AI-powered smart drones is their ability to gather and analyze data frequently. This capacity allows farmers to gain a deeper understanding about the health of their crops, identify potential issues like nutrient deficiencies, pests and diseases early on, and take swift and targeted action. In areas like irrigation management, drones help monitor soil moisture levels across large fields, enabling more efficient water usage.

However, despite their advantages, AI-powered smart drones also face certain limitations. High initial costs and maintenance expenses can make it challenging for small-scale farmers to adopt this technology. Additionally, drones often have limited battery life, requiring frequent recharging, which can be a constraint in covering large fields. On the other hand, AI technology depends heavily on the quality and quantity of data collected, which may be affected by external factors such as weather conditions or equipment malfunctions. Furthermore, managing and operating the drone requires skilled operators with a certain level of technical expertise, which may limit accessibility to some farmers. In the United States, licensing requirements and regulations around restricted airspace present additional barriers. The operators must comply with guidelines and avoid certain zones, especially near populated or sensitive areas. These factors contribute to the need for specialized training and adherence to legal requirements, adding another layer of complexity for farmers considering drone-based solutions.

In conclusion, AI-powered smart drones are transforming agriculture, offering a new level of precision and efficiency. By harnessing these innovations, farmers can increase their productivity and contribute to a more environmentally sustainable approach to farming. As we move into the future, the role of AI and drones in agriculture will undoubtedly expand, paving the way for smarter, more adaptive, and sustainable farming practices that can meet the demands of our changing world.

Conflict of interests

The authors declare that they have no conflict of interests.

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