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The role of drones in smart agriculture ecosystem

Uloga dronova u ekosistemu pametne poljoprivrede

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Abstract

Drone integration in precision agriculture enhances efficiency, sustainability, and resource management. Drones provide high-resolution imaging, real-time data collection, and automated solutions for crop monitoring, irrigation, and pesticide application. The use of drone swarms further optimizes agricultural operations by reducing mission time and enabling large-scale data processing. However, challenges such as regulatory constraints, technological limitations, and high costs remain key barriers to widespread adoption. As drone technology continues to evolve, advancements in AI-driven automation and energy-efficient designs are expected to further enhance their effectiveness in agricultural practices. This paper explores the role of drones in smart agriculture, highlighting their applications, benefits, and advancements within IoT-based farming ecosystems.
Keywords: *precision agriculture, UAVs, smart agriculture, drone swarms, IoT in agriculture*

Sažetak

Integracija dronova u preciznu poljoprivredu poboljšava efikasnost, održivost i upravljanje resursima. Dronovi omogućavaju snimanje u visokoj rezoluciji, prikupljanje podataka u realnom vremenu i automatizovana rešenja za praćenje useva, navodnjavanje i primenu pesticida. Upotreba rojeva dronova dodatno optimizuje poljoprivredne operacije skraćivanjem trajanja misija i omogućavanjem obrade velikih količina podataka. Međutim, izazovi poput regulatornih ograničenja, tehnoloških limitacija i visokih troškova i dalje predstavljaju ključne prepreke za široku primenu. Kako dronovi nastavljaju da napreduju, očekuje se da će integracija veštačke inteligencije i energetski efikasnih rešenja dodatno unaprediti njihovu primenu u poljoprivredi. Ovaj rad istražuje ulogu dronova u pametnoj poljoprivredi, ističući njihove primene, prednosti i inovacije u okviru IoT sistema za poljoprivredu.
Ključne reči: *precizna poljoprivreda, bespilotne letelice (UAV), pametna poljoprivreda, rojevi dronova, IoT u poljoprivredi*

1. Introduction

Smart agriculture leverages digital technologies, data analytics, and automation to improve agricultural productivity and sustainability. As part of this technological shift, drones have emerged as essential tools for real-time field monitoring, precision spraying, and resource management. Their ability to capture high-resolution imagery and analyze environmental conditions allows for optimized decision-making, reducing costs and environmental impact (Mogili & Deepak, 2018; Saiz-Rubio & Rovira-Más, 2020).

Despite their advantages, drone deployment in agriculture faces several challenges, including limited battery life, complex regulatory frameworks, and the need for advanced AI-driven analytics. The development of drone swarms and IoT-integrated solutions presents new opportunities for overcoming these challenges (Qu et al., 2022).

This paper examines the role of drones in modern agriculture, their impact on precision farming, and the prospects of UAV-based agricultural systems. The paper begins with an overview of smart agriculture, highlighting

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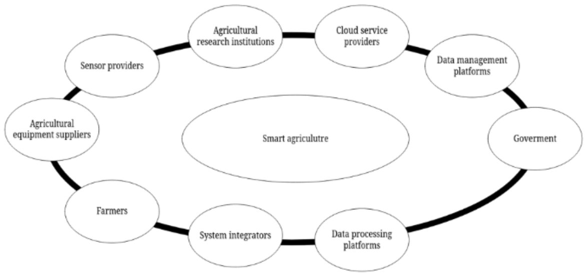
its key components and the role of digital technologies in modern farming. It then explores the use of drones in agriculture, focusing on their core functionalities such as crop monitoring, irrigation management, and pesticide application. The discussion continues with drone swarm technology, emphasizing how coordinated UAV operations enhance efficiency in large-scale farming. This is followed by an examination of drone integration within IoT systems, with a focus on ontology-based frameworks that enable seamless data exchange and automation. The later sections address key challenges and advantages in leveraging drones in precise agriculture. Finally, the conclusion summarizes key findings and suggests potential areas for future research.

2. Smart agriculture as a digital ecosystem

According to IEEE technology predictions for 2025 Smart agriculture (SmartAg) received a B+ rating that suggests its moderate readiness for adoption with moderately high impact on society. Thus, indicating the importance of further development and adaptation of smart agriculture in incoming years. Based on studies and academic literature (Saiz Rubio & Rovira Más, 2020; Srivastava et al., 2024; Walter et al., 2017), smart agriculture is the application of digital technologies, data driven decision making, and automation to enhance agricultural productivity, resource efficiency, and environmental sustainability. It integrates IoT devices, AI based analytics, and precision farming techniques to optimize various aspects of agricultural management. Some studies (Saiz Rubio & Rovira Más, 2020), present Agriculture 5.0 as an extension of smart agriculture, incorporating artificial intelligence (AI) and robotics to autonomously perform essential agricultural tasks. This approach aims to further enhance efficiency, reduce human intervention, and optimize resource utilization.

To fully understand the role of smart agriculture in modern farming, it is essential to look at it as an interconnected ecosystem. Within this ecosystem, service-oriented business models such as sensing-as-a-service, drone-as-a-service, and analytics-as-a-service further accelerate the adoption of digital farming technologies by reducing upfront investment and enabling scalable access to advanced monitoring and decision-support capabilities (Mahroof et al., 2021; Vlachopoulou et al., 2021).

Figure 1. Primary participants of the smart agriculture ecosystem.



Source: Author's

Figure 1 illustrates the primary participants of the smart agriculture ecosystem, highlighting the interconnected relationships among key stakeholders that drive the effective adoption of digital technologies in agriculture:

- Agricultural research institutions - Conduct research, develop innovative technologies, and provide scientific support for smart agriculture practices.
- Cloud service providers - Offer infrastructure for storing and processing large amounts of data collected from sensors, machinery, and other sources (Li et al., 2010).
- Data management platforms - Facilitate the collection, organization, and analysis of agricultural data to optimize decision making.
- Government - Plays a regulatory and supportive role by setting policies, providing subsidies, and encouraging the adoption of smart agriculture technologies.
- Data processing platforms - Utilize advanced analytics, artificial intelligence, and big data techniques to transform raw data into actionable insights.
- System integrators - Ensure the seamless integration of various technologies, enabling interoperability between different components of the smart agriculture ecosystem (Davies et al., 2007).
- Farmers - The primary users of smart agriculture technologies, leveraging data driven insights to improve productivity and sustainability.
- Agricultural equipment suppliers - Provide advanced farming machinery, automated systems, and precision agriculture tools to enhance efficiency.
- Sensor providers - Develop and supply IoT based sensors that monitor soil conditions, crop health, weather patterns, and other environmental factors.

Within such a digital ecosystem, drones occupy a particularly important role because they connect aerial sensing, spatial data acquisition, and targeted intervention capabilities with broader agricultural data flows. Their ability to support both observation and actuation makes them one of the most versatile technological components of smart agriculture

3. Drone technologies and applications in smart agriculture

Among the enabling technologies of smart agriculture, drones have emerged as one of the most versatile platforms due to their ability to rapidly collect high-resolution field data and support targeted agricultural operations. Unmanned aerial vehicles (UAVs), also referred to as drones, may operate autonomously or remotely and can differ in size, configuration, payload, and mission profile depending on the intended agricultural task. Their flexibility makes them especially suitable for precision agriculture, where timely observation and localized intervention are essential for improving productivity and resource efficiency (Hassanalian & Abdelkefi, 2017; Mogili & Deepak, 2018).

Figure 2. Drones during agricultural missions

Sources: user6702303 (n.d.), Freepik, https://www.freepik.com/free-photo/drone-spraying-fertilizer-vegetable-green-plants-agriculture-technology-farm-automation_36681035.htm; ArthurHidden (n.d.), Freepik, https://www.freepik.com/free-photo/white-drone-hovering-bright-blue-sky_6659450.htm

An important extension of individual UAV operation is the use of drone swarms, in which multiple aerial vehicles cooperate to accomplish a shared mission. In agriculture, this approach is especially relevant for large fields and time-sensitive tasks, since coordinated UAVs can map areas in parallel, support repeated low-altitude imaging, and improve the efficiency of operations such as disease detection, phenotyping, and large-scale field observation. At the same time, swarm deployment introduces additional implementation challenges, including coordination, communication, resource allocation, mission planning, and scalability in complex environments (Ming et al., 2023; Qu et al., 2022; Tahir et al., 2019).

The most widespread agricultural applications of drones are related to field monitoring and sensing. Equipped with RGB, thermal, and multispectral sensors, UAVs support crop health assessment, land mapping, irrigation monitoring, and the detection of anomalies that would be difficult to identify quickly through conventional field inspection alone. In the reviewed literature, crop monitoring, irrigation management, and precise pesticide-related observation appear consistently as core agricultural uses of drones (Dutta & Goswami, 2020; Mogili & Deepak, 2018; Nazarov et al., 2023).

In addition to observation, drones can also support direct agricultural interventions. The literature shows two particularly visible directions: precision spraying and specialized aerial seeding. UAV-based spraying reduces manual exposure and enables more localized application of pesticides and related inputs, while recent research on aerial seeding has demonstrated specialized self-burying seed carriers intended for deployment from the air, particularly in hard-to-reach or degraded terrain (Luo et al., 2023; Mogili & Deepak, 2018).

Overall, drone technology offers significant benefits for smart agriculture in terms of efficiency, precision, and data availability. However, wider adoption depends not only on technical performance, but also on implementation barriers, economic feasibility, and operator preparedness. Comparative and adoption-oriented studies show that UAV diffusion in agriculture remains shaped by regulatory, technical, operational, social, and behavioural constraints, while training and competence development remain important conditions for safe and effective deployment (Nazarov et al., 2023; Puppala et al., 2023; Schmidt et al., 2022).

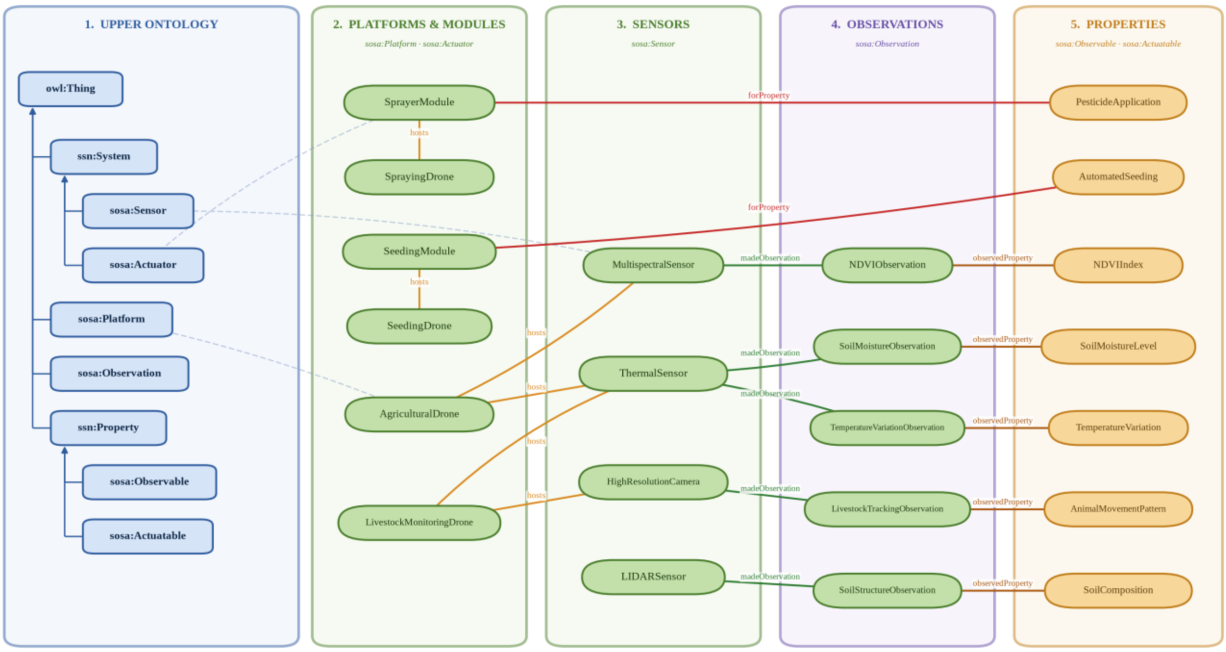
4. Drones as a part of IoT agricultural systems

As the role of drones in smart agriculture expands from isolated monitoring and intervention tasks to participation in broader data-driven workflows, their integration into IoT-based agricultural systems becomes increasingly important. In previous implementation-oriented work, drone deployment in agricultural environments was examined through the combination of simulated flight settings, real-time sensor inputs, and IoT connectivity. By linking hardware components such as temperature, humidity, and air-quality sensors with software frameworks including ROS2 and Gazebo, that work demonstrated how drones can support continuous data collection, analysis, and system responsiveness in agricultural scenarios (Joksimović et al., 2024).

However, technical integration alone is not sufficient when multiple platforms, sensors, actuators, and data-processing services must interact in a consistent and reusable way. For that reason, a standards-compliant semantic model is needed in order to formally describe system components, their functions, and the relationships among them. The model presented in Figure 3 addresses this need by formalizing interactions among drones, actuators, sensors, and the observations they produce, thereby improving interoperability and supporting more structured data exchange in complex agricultural workflows (Cox, 2017; Haller et al., 2018).

Figure 3 applies the SOSA and SSN standards (Compton et al., 2012; Janowicz et al., 2019) to represent different drone roles without modifying the underlying ontology classes. Instead, the model introduces concrete individuals that illustrate how drones may operate either as sensing platforms or as carriers of actuation modules. In this way, the ontology does not remain at an abstract level, but reflects realistic agricultural scenarios in which drones collect field data, support intervention tasks, and exchange information with other components of a digital farming environment.

Figure 3. Ontology based on SOSA/SSN for drones in smart agriculture



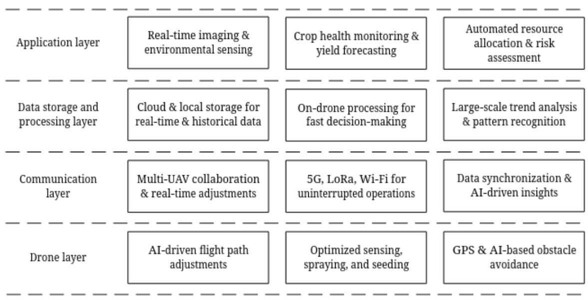
Source: Author's model based on SOSA/SSN ontology (Cox, 2017; Haller et al., 2018)

At the actuation level, the model includes the SprayingDrone and SeedingDrone, both represented as instances of sosa: Platform. These platforms host actuator modules modeled as instances of sosa: Actuator, with their operational purpose linked to agricultural properties through ssn: forProperty. More specifically, the SprayerModule is associated with pesticide application, while the SeedingModule is related to automated seeding. Through these relations, the model makes explicit how drones can participate not only in observation, but also in direct intervention processes such as treatment delivery and seed deployment (Haller et al., 2018).

At the sensing level, the ontology models the AgriculturalDrone as a platform hosting a MultispectralSensor and a ThermalSensor, both represented as sosa: Sensor instances. These devices are linked to observations such as TemperatureVariationObservation, NDVIObservation, SoilMoistureObservation, and each connected to a corresponding observed property. In a similar way, the LivestockMonitoringDrone is represented as a sensing platform equipped with a HighResolutionCamera and a ThermalSensor in order to support monitoring of animal movement and activity. By using relations such as sosa: hosts, sosa: madeObservation, and sosa: observedProperty, the ontology clarifies which device is hosted by which drone, what kind of observation is produced, and which agricultural or livestock-related property is being observed.

The value of this ontology-based representation lies in the fact that it provides a semantically consistent view of drone-enabled agricultural processes. Rather than describing each drone function in isolation, the model captures platforms, hosted modules, observations, and target properties within a shared conceptual structure. This makes the proposed system easier to interpret, extend, and potentially integrate with other IoT-oriented agricultural services in future work. In that sense, the ontology should be viewed as a semantic consolidation of implementation-relevant entities and interactions, rather than merely as a diagrammatic abstraction.

Figure 4. Layered IoT architecture for drones in precision agriculture



Source: Author's

Figure 4 complements this semantic view by presenting the same ecosystem from an implementation perspective through a layered IoT architecture. While Figure 3 explains how entities and relations are formally represented, Figure 4 shows how drone-based sensing and actuation can be organized across the application layer, data storage and processing layer, communication layer, and drone layer. The drone layer includes field-level operations such as autonomous navigation, precision resource application, and AI-supported flight optimization. The communication layer enables data exchange through technologies such as 5G, LoRa, and Wi-Fi. Above that, the storage and processing layer supports cloud and edge-based analysis, while the application layer transforms processed data into decision-support functions relevant to agricultural management (Joksimović et al., 2024).

Taken together, Figures 3 and 4 describe two complementary aspects of the same system. Figure 3 provides the semantic structure needed for interoperability and conceptual consistency, whereas Figure 4 illustrates how those semantically defined entities can participate in a practical IoT workflow. This dual perspective is particularly relevant in smart agriculture, where efficient system performance depends not only on sensing and actuation capabilities, but also on the reliable coordination of communication infrastructure, data-processing services, and decision-support applications.

4. Challenges in the application of drones in smart agriculture

Table 1 summarizes the key advantages, implementation challenges, and emerging directions associated with the use of drones in smart agriculture.

Table 1. Key advantages, challenges, and future considerations of drones in smart agriculture

Aspect	Advantages	Challenges
Regulations and ethical considerations	- Can support more structured and accountable drone deployment - Encourages clearer data-governance and operational standards	- Privacy, surveillance, and environmental concerns remain significant - Regulatory fragmentation limits wider deployment
Farmer adoption	- Improves resource utilization and farm efficiency - Real-time data supports better decision-making - Specialized training programs encourage acceptance	- Costs of purchasing and maintaining drones remain high - Skill gaps and limited digital literacy in rural communities - Insufficient technological infrastructure, especially in developing regions
Technological capabilities	- Enables immediate crop, soil, and weather assessment - Advanced sensors can detect diseases or anomalies quickly - Automates repetitive tasks, saving labor	- Short battery life limits coverage - Restricted payload capacity constrains certain tasks - Data accuracy can be affected by varying environmental conditions
Emerging directions	- AI & Machine Learning: Enhances predictive analytics - Drone Swarms: Coordinated coverage of large fields - Harvesting Drones: Potential to reduce labor demands - Micro-Drones: Ideal for vertical farming and greenhouses	- Complex swarm management and communication - Battery and carrying limitations for harvesting tasks - AI models must adapt to diverse farming conditions

Source: Authors synthesis based on the reviewed literature (Fue et al., 2020; Ming et al., 2023; Nazarov et al., 2023; Puppala et al., 2023; Schmidt et al., 2022; Spaans et al., 2024; Vrochidou et al., 2022)

The overview presented in Table 1 shows that the use of drones in smart agriculture cannot be evaluated only through their technical capabilities. Although the literature consistently emphasizes their value for real-time monitoring, precision intervention, and improved resource efficiency, the broader adoption of these systems depends on a combination of regulatory, economic, infrastructural, and educational factors. In particular, high acquisition and maintenance costs, limited digital skills, and insufficient rural connectivity remain substantial barriers to implementation. At the same time, emerging directions such as AI-driven analytics, drone swarms, and specialized drone platforms expand the technological potential of these systems, while also increasing the complexity of coordination, energy management, and operational reliability. Therefore, the future of drone-enabled smart agriculture depends not only on technological progress, but also on the development of supportive policies, interoperable digital infrastructures, and stakeholder readiness for adoption.

5. Discussion

The analysis shows that the contribution of drones to smart agriculture becomes more meaningful when drone-supported tasks are not viewed as isolated operations, but as interconnected elements of a broader digital system. While activities such as crop monitoring, spraying, irrigation support, and livestock observation are often discussed separately in the literature, the findings of this paper suggest that their practical value increases when they are interpreted through relations among platforms, sensors, actuators, observations, and target agricultural properties. From that perspective, the proposed ontology-based model helps shift the focus from individual drone functions to the structure of interactions that make smart agriculture systems more coherent and interoperable.

Compared with many existing approaches in the literature, which primarily focus on specific drone applications, technical performance, or economic and operational benefits, the approach presented in this paper places greater emphasis on interoperability and conceptual integration. Earlier studies have extensively addressed the use of drones in precision agriculture, especially in relation to monitoring, spraying, and field analysis, but ontology-oriented and system-level representations are less frequently treated as central contributions (Mogili & Deepak, 2018; Nazarov et al., 2023). In this sense, the proposed model extends the discussion beyond standalone drone functions by linking them with semantic modeling principles derived from the SOSA/SSN framework (Cox, 2017; Haller et al., 2018).

Practical implications of the proposed model are particularly relevant for several stakeholder groups within the smart agriculture ecosystem. For agricultural research institutions and system integrators, the model can support the design, comparison, and extension of interoperable drone-enabled solutions and experimental prototypes. For cloud, data management, and processing platforms, as well as for suppliers of agricultural equipment and sensors, it provides a clearer conceptual basis for integrating heterogeneous devices, services, and data flows into a shared digital environment. For governments and policy actors, such models may contribute to more structured digital agriculture strategies and interoperability-oriented governance frameworks. For farmers, although the ontology itself is not a direct operational tool, its indirect value lies in enabling more integrated, understandable, and potentially scalable smart agriculture solutions that support monitoring, decision-making, and more efficient use of agricultural resources.

At the same time, several limitations of this work should be acknowledged. First, although the proposed ontology was not developed in isolation and is conceptually grounded in earlier implementation-oriented work involving simulation, real-time sensor integration, and IoT connectivity, the ontology itself has not yet been validated through operational agricultural field deployments (Joksimović et al., 2024). Second, the model remains illustrative in scope, since it focuses on selected drone roles, sensors, actuators, and observations rather than covering the full diversity of agricultural technologies and scenarios. Third, although the layered architecture provides an implementation-oriented perspective, actual deployment would still depend on factors such as connectivity, infrastructure, regulation, cost, and user readiness, which remain significant barriers to broader adoption (Puppala et al., 2023; Schmidt et al., 2022). These limitations suggest that the proposed framework should be understood as a foundation for further validation and extension, rather than as a complete operational solution.

6. Conclusion

This paper examined the role of drones in the smart agriculture ecosystem through a review of their main applications, including crop monitoring, precision spraying, irrigation support, seeding, and livestock observation. In addition to reviewing these application areas, the paper proposed an ontology-based model grounded in the SOSA/SSN framework and presented a layered IoT architecture in order to describe how drones, sensors, actuators, and observations can be integrated within a broader digital agricultural system.

The results of the study indicate that drones have significant potential to improve efficiency, sustainability, and data-driven decision-making in agriculture. The analysis showed that their value does not lie only in individual operational tasks, but also in their integration into wider IoT-enabled workflows. In this sense, the proposed semantic model contributes to a more structured and interoperable understanding of drone-enabled agricultural processes, while the layered architecture provides an implementation-oriented perspective on how such systems may function in practice. At the same time, the review also confirmed that wider adoption remains limited by regulatory, economic, infrastructural, and technological barriers.

Future research should focus on the real-world validation of the proposed ontology through drone deployments in operational agricultural environments. Such validation should include the preparation of ontology-based semantic scenarios and their evaluation by both agricultural domain experts and ontology specialists. In addition, the model should be extended to represent sensor data streams and their interactions in greater detail, using data collected during future drone field trials.

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