

DOI: 10.34185/1991-7848.itmm.2026.01.080

ARCHITECTURAL PATTERNS OF IOT SYSTEMS IN SMART AGRICULTURE

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Abstract. *The rapid growth of Internet of Things (IoT) technologies in agriculture has increased the need to understand how these systems are designed. This paper analyzes IoT system architectures used in smart agriculture, with a focus on layered models. A set of 18 research articles describing real IoT systems was reviewed. Based on this analysis, three main architecture types were identified: three-layer, four-layer, and five-layer models. The results show that the four-layer architecture is the most commonly used, as it provides better scalability and supports distributed systems through the use of a gateway or edge layer. In addition to layered models, several design patterns that correspond to specific system needs were identified. These patterns extend system functionality but do not replace the base architecture. The results show that the choice of architecture depends on system scale and requirements, and this choice has a direct impact on system performance and scalability.*

Keywords: *Internet of Things, precision agriculture, IoT architecture, layered architecture, design patterns, smart farming.*

Introduction. The popularity of Internet of Things (IoT) technologies has grown exponentially in recent years. IoT is adopted to automate recurring operations, improve monitoring, optimize resource use, and support data-driven decision-making. As a result, IoT has been integrated into numerous diverse sectors. Tasks that were performed manually before are now automated through IoT systems. One of the biggest fields that has recently adopted IoT is agriculture. The integration of these technologies has become one of the key drivers of precision agriculture digitalization. The exact implementations of IoT in agriculture vary from simple irrigation systems to complex monitoring and management frameworks. At the very core of IoT systems lies their architectural design, which determines how sensing devices, communication networks, processing layers and user interfaces are organized. The choice of architecture for a particular system depends on multiple

factors and impacts core system parameters, such as scalability, reliability, latency and energy efficiency.

Results and Discussion. Conceptual models of IoT systems are often described using a layered approach. The most popular architecture types are three-layer, four-layer and five-layer architectures. Each new layer represents another explicit level of responsibilities extracted from previous layers. It is a structured way to organize system components into sensing, networking, computing and application layers.

While theoretical layer-based architecture type division is important for the separation of concerns and enhanced scaling capabilities, the exact layer implementation may differ among similar systems. For instance, a gateway network layer configuration is vastly different from its fog computing analogue. It is very important to understand the difference between a layered architecture framework and its implementation, as well as how specific paradigms, such as edge computing, microservices, or other design approaches, are integrated into layered models.

To better understand the practical side of architectures and their connection to their actual implementations, a set of 18 articles, each describing a different IoT system in the smart agriculture field, was reviewed. These articles represent IoT systems ranging from simple irrigation systems to complex microservice-based monitoring frameworks. Although the reviewed set is not exhaustive, its diversity makes it possible to identify the dominant architectural tendencies and recurring design patterns in smart agriculture IoT systems.

The main components that make up an average smart agriculture IoT system are the perception, network and application layers. The perception layer is responsible for physical sensors, such as soil moisture probes, thermocouples, nutrient analyzers and other specialized sensor units. The network layer coordinates the flow of the acquired sensory data. The application layer provides user-facing services and system interaction, while data storage and analytics may be implemented either within this layer or in dedicated processing components, depending on the system architecture. Since these three main components are the bare minimum for a functional automated IoT system, they naturally make up a three-layer architecture, which is mainly used in prototype systems where a single

unit communicates directly to the cloud or an application. In the analyzed literature, the three-layer architecture is mainly used in small-scale implementations and prototypes [1-2], accounting for around 28% of cases.

The four-layer architecture extends this model by introducing a dedicated buffer layer between the sensing nodes and the cloud service. This solves the problem of unreliable and inefficient direct connectivity. The resulting structure is made up of perception, network, edge controller and application layers. Though the perception and application layers stay the same as in the three-layer architecture, the addition of the edge controller layer, coupled with the overhauled networking layer, vastly improves the system's scalability and reliability. The edge controller introduces a dedicated layer for sampling, scheduling, data buffering and preprocessing, while the network layer is now responsible for the flow of sensory data to the edge controllers and aggregation of acquired results. This structure is widely used in actual IoT field monitoring/irrigation systems [3-4], where networks cover field sizes of tens or hundreds of hectares and are utilized in around 67% of cases.

With the rapid development and popularization of microservice architecture in the software engineering domain [5], other fields, including precision agriculture, have begun to adopt its principles of separation of concerns and enhanced scalability. Systems that implement a five-layer architecture with perception, network, processing, application and business layers are generally decomposed into microservices instead of being combined into one monolithic application. This approach enables high scalability and allows the replacement of any component without redesigning the entire system. Microservice-based five-layer architecture is usually represented by systems implementing digital twins as a virtual representation of physical conditions with predictive modeling support [6]. Because of the sheer amount of work required for development and the scale required to justify this amount of work, systems like this are underrepresented, with only 6% of use cases. A short summary of base architecture types is presented in tab. 1.

Table 1

Architecture types and associated patterns observed in the reviewed sample

Architecture	Articles count	System scale	Core layers	Common design patterns
Three-layer	5	Small-scale, prototypes	Perception, network, application	Event-driven
Four-layer	12	Field-scale	Perception, network, edge, application	Edge computing, fog computing
Five-layer	1	Enterprise	Perception, network, processing, application, business	Microservices, digital twins

Conclusion. Based on a structured review of a set of 18 published IoT implementations, the diverse architectural frameworks used in smart agriculture were identified. Three-layer, four-layer and five-layer architectures serve as the dominant organizational framework, with each tier representing a more complex and better-scaled layer. The three-layer architecture, implemented in 28% of the cases, is typically used for small prototype or proof of concept systems, where sensing nodes have direct communication with a cloud or application. The four-layer architecture, which is the most common and accounts for approximately 67% of the reviewed cases, improves system scalability by introducing a dedicated edge controller layer. The five-layer architecture, while being used only in 5% of cases, provides the highest degree of modularity/scalability for large-scale systems, allowing it to be used in enterprise level systems.

Beyond base layered architecture types, a set of additional design patterns was found. Edge computing, fog computing, digital twins and event-driven approaches are independent patterns that can be combined with base architecture approaches to address specific needs of a particular system. Matching the system's architecture with its functional needs is crucial for proper system architecture selection. This early decision is critical for a system's efficiency, maintainability and future scalability.

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АРХІТЕКТУРНІ ПАТЕРНИ ПОБУДОВИ ІОТ-СИСТЕМ У РОЗУМНОМУ СІЛЬСЬКОМУ ГОСПОДАРСТВІ

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Анотація. Швидке зростання використання технологій Інтернету речей (IoT) в сільському господарстві зумовило потребу в кращому розумінні того, як проєктуються такі системи. У цій роботі проаналізовано архітектури IoT-систем, що застосовуються в розумному землеробстві, з акцентом на багаторівневі моделі. Було розглянуто 18 наукових публікацій, які описують реальні IoT-рішення. За результатами аналізу виділено три основні види архітектур: трирівневу, чотирирівневу та п'ятирівневу. З'ясовано, що найпоширенішою є чотирирівнева архітектура, оскільки вона забезпечує кращу масштабованість і підтримує розподілені системи за допомогою крайового рівня. Окрім базових багаторівневих моделей, визначено також додаткові шаблони проєктування, що відповідають окремим потребам систем. Ці підходи розширюють функціональність, але не замінюють базову архітектуру. Отримані результати показують, що вибір архітектури залежить від масштабу системи та її вимог і безпосередньо впливає на продуктивність і масштабованість.

Ключові слова: Інтернет речей, точне землеробство, архітектура Інтернету речей, багатопарова архітектура, розумне сільське господарство.

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