A scalable smart irrigation system based on Internet of Things technologies

Carlos Chillón Geck and Rami Nasr
Institute of Digital and Autonomous Construction, Hamburg University of Technology, Blohmstraße 15, 21079 Hamburg, Germany
E-mail: carlos.chillon.geck@tuhh.de

Abstract: Internet of Things (IoT) technologies have reduced the need for manual labor in agriculture by facilitating the automation of irrigation processes. To automate irrigation, IoT-based irrigation systems consisting of low-cost hardware components have been proposed, aiming at optimizing irrigation and reducing overall costs. However, the design of IoT-based irrigation systems is based on ad-hoc solutions that lack scalability and integration capabilities. This paper presents a scalable smart irrigation system based on IoT technologies, developed using the OPC Unified Architecture (OPC UA). The system includes low-cost hardware components with embedded computing and IoT communication capabilities as well as an open-source IoT platform, which is validated in a laboratory test. The results of the validation test highlight the effectiveness of the scalable smart irrigation system in enhancing water resource management and operational efficiency.

Keywords: Smart irrigation, Internet of Things, OPC UA, scalable systems.

Erschienen in Tagungsband 35. Forum Bauinformatik 2024, Hamburg, Deutschland, DOI: 10.15480/882.13494

1 Introduction

As the global population continues to grow, projected to surpass 8.5 billion by 2030, the challenges of food security and water scarcity become more pronounced [1]. Thus, innovative irrigation solutions in agriculture are essential to meet the increasing food demands and to ensure sustainable agricultural practices. In particular, wireless sensor networks and Internet of Things (IoT) technologies have reduced the need for manual labor, making automation in agriculture more feasible [2]. Numerous studies on precision agriculture and smart irrigation systems have explored different approaches to enhance water efficiency [3]. Several studies proposed low-cost IoT-based prototypes that optimize water usage through automatic control of irrigation based on soil moisture and environmental conditions for intelligent scheduling [4]. Yet, research often overlooks scalability and integration aspects into irrigation systems. Ensuring compatibility among different hardware components is crucial to achieve flexibility that supports diverse infrastructures, ranging from agricultural farms to urban gardening. Scalable systems may be adapted to various agricultural operations, from small farms to large plantations, and it may be easily upgraded when operations expand. Integration with diverse technologies, such as drones and satellite imaging, also requires scalability and integration among different technologies for effective decision-making.

Few studies focus on scalability and integration in smart irrigation. For example, IoT with aerial mapping technologies using mesh networks for sensor communication and cloud computing for data processing and storage have been proposed [5], also including data from wireless sensor networks for precision agriculture [6]. Other research focuses on automating irrigation with multi-agent systems [7], which inherently enable scalability by managing an increasing number of sensors and agents [8]. However, scalability and integration are not explicitly addressed. To address this gap, in this paper, the OPC Unified Architecture (OPC UA) is adopted to implement a scalable smart irrigation system using IoT technologies. OPC UA provides a framework for integrating devices and systems across manufacturers and communication protocols [9]. By leveraging an OPC UA server, scalability is explicitly addressed, structuring data and communication. OPC UA enhances scalability and facilitates asset integration, allowing smart irrigation systems to adapt and expand to meet evolving demands and technological advancements.

2 Design of a scalable smart irrigation system

2.1 System requirements

In Table 1, the functional requirements that define the operational capabilities of a scalable smart irrigation system are summarized. Requirements not directly related to scalability are (1) actuators enabled by automated control algorithms, (2) user-friendly interfaces with features including visualization of information for decision-making, data querying and analysis features, alerts for system fault detection, and (3) efficient data storage. Moreover, non-functional requirements are considered for developing of the system include cost efficiency and security.

Table 1: Functional requirements of a scalable smart irrigation system.

Requirements	**Description**
Semantic richness	Semantically enrich data with metadata and context to enable comprehensive understanding of irrigation data and instantiatino of system elements based on a formal asbtract model.
Data integration	Collect data from various devices, including a robust data ingestion connector, designed to interface with specified external communication protocols for collecting real-time data from various sources.
Scalability and modularity	Provide scalability, capable of expanding to accommodate additional sensors or devices without significant modifications to the core system architecture.

2.2 System architecture

The system architecture is defined based on the requirements listed above. The proposed system integrates an OPC UA framework into an IoT layered architecture using standard information modeling. In Figure 1, the interconnected system layers are illustrated, encompassing agents, each of which devised to solve specific tasks:

- *Assets layer*: The physical components, such as sensor nodes and actuators, are interfaced with the digital system.
- *Integration layer*: In this layer, embedded software standardizes the raw data collected by sensors into a consistent format for further processing.
- *Communication layer*: Receives information on which data must be collected and uses standard protocols for data communication.
- *Information and aggregation layer*: The OPC UA server is the centerpiece of this layer. OPC UA employs an information model, serving as a schema to standardize the sensor data. The information model enables integrating sensor data regardless of the source and format and facilitates model instantiation.
- *Functional layer:* In this layer, the data is stored and irrigation schedules are created, which are then executed to control the irrigation process efficiently.
- *Business layer:* Translates the operational efficiencies into business value, producing visual analytics for strategic planning and decision-making. Real-time ("live") monitoring and the ability to override automated decisions are provided through a dashboard.

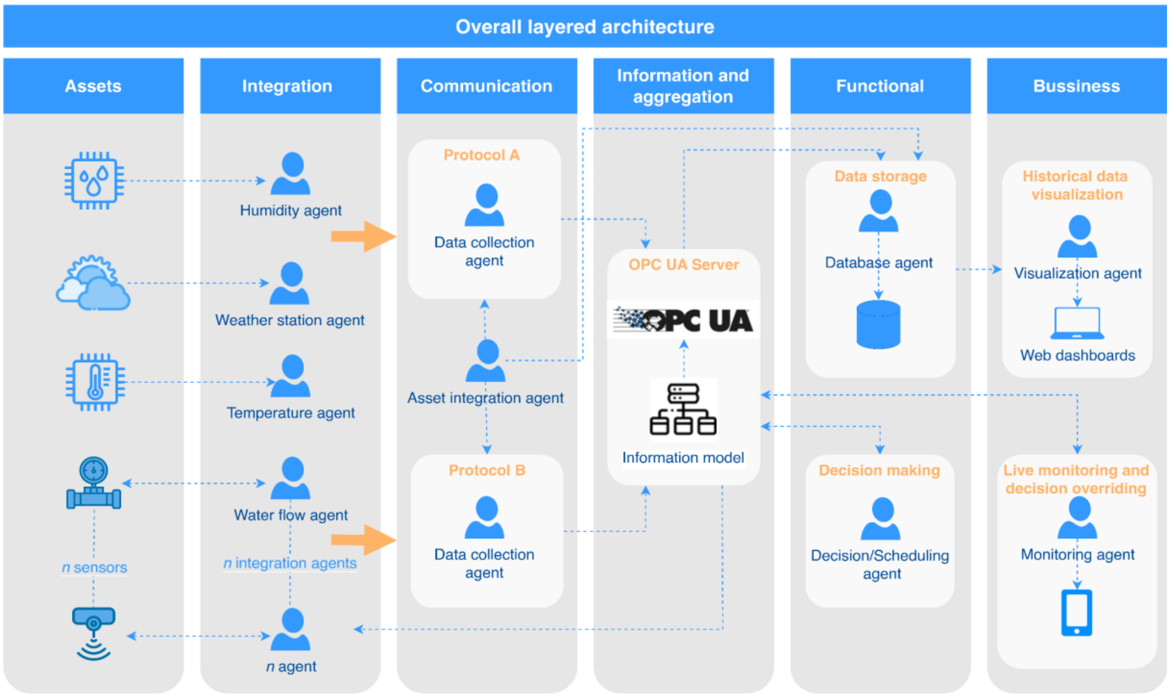

Figure 1: Layered architecture of the smart irrigation system.

3 Implemention of the smart irrigation system

This section describes the protototype implementation of the smart irrigation system, with emphasis of the agents situated in the different layers intoroduced above.

3.1 Assets and integration layer

The assets layer encompasses the hardware used to create the smart irrigation system. For implementation, the hardware components listed in Table 2 are used with a pump and relays. The ESP-32 S3 microcontrollers handle real-time data collection from the sensors and control the actuators based on the input signals received from the Raspberry Pi. The integration layer is where diverse sensors represented by dedicated agents, in which a Raspberry Pi serves as the central hub, aggregating data from the microcontrollers, running decision-making algorithms, and providing a user interface for monitoring and control. The integration layer employs common industrial communication protocols, such as message queuing telemetry transport (MQTT) for lightweight and efficient messaging, to forward standardized and semantically enriched data to the communication layer. The hardware components are chosen with respect to reliability, cost-effectiveness, and compatibility with IoT-based smart irrigation systems.

Table 2: Hardware components, as part of the asset layer.

Component	**Quantity**	**Purpose**
AZ Delivery v1.2 capacitive soil moisture sensor	2	Measure and monitor the soil humidity levels.
Analog devices DS18B20 temperature sensor	2	Measure and monitor the soil temperature levels.
Sparkfun HC-SR04 ultrasonic sensor	1	Measure and monitor the water level in the tank.
DNT weather station pro	1	Collect environmental data.
WHADDA 12 V solenoid valve	3	Control the flow of water.
Espressif ESP32 S3 microcontroller	2	Primary acquisition and control units for sensors and actuators.
Raspberry Pi 4 Model B 4 Gb	1	Central processing unit for system management, data processing and visualization.

3.2 Communication layer

Communication agents enable data transfer from the integration layer to the information and aggregation layer. Data is ingested and mapped to the OPC UA server. The communication flow is initiated by a JSON file, that serves as a guiding schema for the data collection agents, detailing key elements for the system operation. The data description file (i) specifies the communication protocol to trigger the relevant data collection agent, (ii) enumerates data points, (iii) lists node IDs to map data onto the relevant variable nodes in the OPC UA server, and (iv) describes the structure for data storage within the database. The JSON file guides the data flow from the integration layer to subsequent layers, ensuring cohesive system operation.

3.3 Information and aggregation layer

The OPC UA server that hosts the information model lies in the information and aggregation layer, serving as the foundation of the smart irrigation system architecture. The foundation of the scalability of the system lies in the design of an OPC UA *types model*. The types model enables instantiation of OPC UA *instance models*, facilitating the system to accommodate an expanding array of assets and subsystems for defining a wide range of generic object types, variable types, data types, interface types, and standardized hierarchal relations and information models. Thus, to model a new scalable smart irrigation system, four key categories, i.e. *Actuators*, *Sensors*, *WeatherData*, and *IrrigationControl* are required. A UML schema of the scalable smart irrigation system implemented in this work is shown in Figure 2.

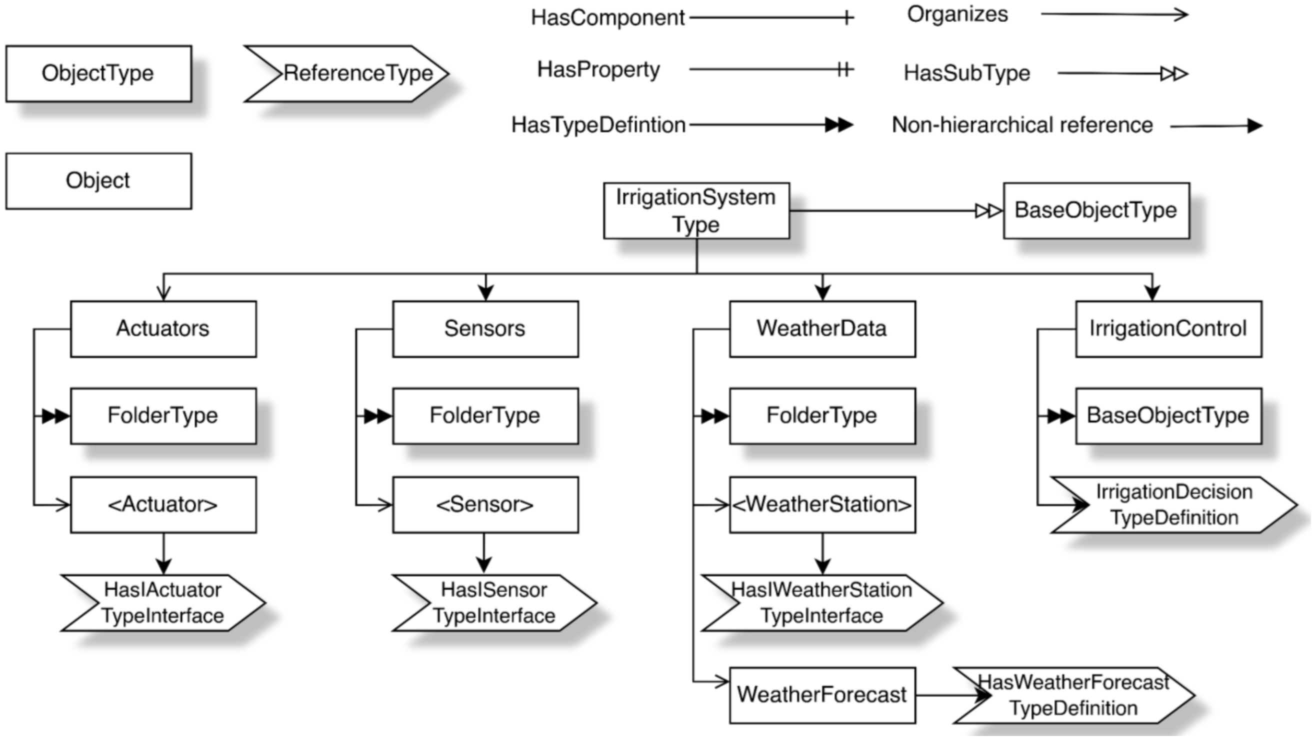

Figure 2: Schema of the scalable smart irrigation system.

3.4 Functional layer

In this layer, the database agent, hosted on Node-RED, is responsible for the systematic storage of data to InfluxDB that is hosted as a local instance on the Raspberry Pi. The decision agent processes data from the OPC UA server to determine the most efficient irrigation schedules and triggers the irrigation process. The event-based control algorithm, implemented in Python and running on the Raspberry Pi, considers minimum soil moisture levels and weather forecasts.

3.5 Business layer

To facilitate the visualization of historical data, Grafana, an open-source web service for data analytics, is hosted on the Raspberry Pi. The Grafana dashboard displays various metrics related to soil moisture, temperature, water levels, and irrigation schedules. Historical data can be accessed and visualized, enabling analysis of past irrigation events and environmental conditions. Historical data visualization allows for trend analysis, performance monitoring, and compliance reporting, enabling users to make informed decisions based on past patterns and system performance. In addition, a manual override option allowing user control to intervene when the irrigation system does not function as expected.

4 Validation of the smart irrigation system

Validation tests are conducted using two prototype implementations of the smart irrigation system, (i) system 1 (S_1), an indoor setup without consideration of weather forecasting, and (ii) system 2 (S_2), an indoor setup that considers outdoor conditions with weather forecasting. Both systems, implemented in compliance with the above specifications, are planted with garden cress and are supposed to have optimal soil humidity levels of 70%, which is the optimal soil moisture for garden cress growth. The soil moisture sensor provides consistent moisture readings within an accuracy range of ±4% and a response time of under 1.5 s for detecting moisture changes.

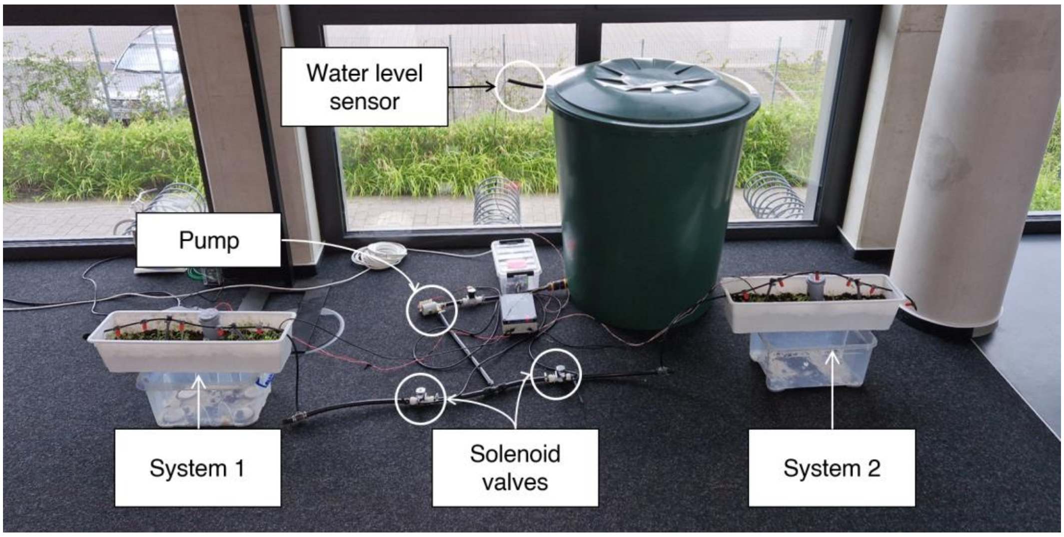

Figure 3: Validation test setup.

System S_1 is designed to maintain the soil humidity at the desired level through automated irrigation. The validation process involves monitoring soil humidity, water consumption, and the growth of garden cress over a 10-day period. The soil humidity sensors continuously measure the moisture content in the soil, and data is collected and analyzed to ensure the system maintained the daily soil humidity at the optimal level of 70%. The total water used by the system is 2.21 l. The growth of garden cress is monitored as an indicator of the system effectiveness, and the garden cress reached a height of 12 cm. Figure 4 illustrates the soil humidity of System S_1 over the 10-day period.

System S_2 incorporates weather forecasting to adjust irrigation schedules based on predicted rainfall, aiming to optimize water usage. Although the setup is implemented indoors for validation purposes, it considers outdoor conditions to validate the effect of integrating weather data. Soil humidity is maintained at 70%, such as with system S_1, but system S_2 adjusts irrigation based on real-time sensor data and weather forecasts. The total water used by system S_2 is 1.92 l, showing a reduced water consumption in comparison to S_1. The growth of garden cress is monitored as an indicator of the system effectiveness, reaching a height of 9 cm, 3 cm smaller than the cress used in S_1, arguably due to the smaller amount of water. Figure 5 illustrates the soil humidity of S_2 over the 10-day period.

IrrigationHistory

```
2024-06-20T02:55:29.504Z
2024-06-20T03:56:00.567Z
2024-06-21T02:58:36.543Z
2024-06-22T02:57:50.266Z
2024-06-23T02:58:45.333Z
2024-06-25T02:00:11.647Z
```

Figure 4: Soil humidity and total water consumption of S_1.

IrrigationHistory

```
2024-06-18T10:53:04.020Z
2024-06-19T02:54:28.465Z
2024-06-20T02:55:41.565Z
2024-06-20T03:56:06.630Z
2024-06-21T02:57:00.601Z
2024-06-22T02:58:02.301Z
```

Figure 5: Soil humidity and total water consumption of S_2

5 Summary and conclusions

This paper has presented a scalable smart irrigation system to enhance water resource management and operational efficiency. The system integrates IoT-based hardware components, including sensor nodes, actuators, a weather station, and IoT platforms. The novelty of the system lies in integrating an OPC UA framework into an IoT layered architecture using formal information models. Thus, the smart irrigation system can be scaled to adapt to agricultural fields or urban gardening applications. Two prototype implementations of the system have been validated, using outdoor conditions using weather forecasts and indoor conditions. In the validation tests, optimal soil moisture levels have been kept, demonstrating the effectiveness of the system to irrigate without human intervention. The OPC UA framework ensures semantic richness, standardized data, and efficient instantiation of new elements of the system. Future research may integrate machine learning to improve control algorithms for different setups and deployment in real agricultural or urban environments, including different sensors and actuators to validate the scalability and integration capabilities of the system, which in this paper is shown in an indoor environment.

References

[1] M. van Dijk, T. Morley, M. L. Rau, & Y. Saghai, “A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050,” Nat Food, 2(7), pp. 494-501, 2021

[2] V. V, R. A. C, V. S. R. R, A. K. P, S. M. R, and S. B. M, “Implementation of IoT in Agriculture: A Scientific Approach for Smart Irrigation,” in 2022 IEEE 2nd Mysore Sub Section International Conference (MysuruCon), pp. 1-6, 2022

[3] H. Osman, M. Mahmud, A. Hassan, & A. Ali, “A bibliometric analysis of the evolution of IoT applications in smart agriculture,” Ingénierie des systèmes d information, 28, pp. 1495-1504, 2023

[4] O. Friha, M. A. Ferrag, L. Shu, L. Maglaras, & X. Wang, “Internet of Things for the Future of Smart Agriculture: A Comprehensive Survey of Emerging Technologies,” IEEE/CAA Journal of Automatica Sinica, 8(4), pp. 718–752, 2021

[5] C. Cambra, S. Sendra, J. Lloret, & L. Garcia, “An IoT service-oriented system for agriculture monitoring,” in 2017 IEEE International Conference on Communications (ICC), pp. 1–6, 2017

[6] P. Sanjeevi, S. Prasanna, B. Siva Kumar, G. Gunasekaran, I. Alagiri, & R. Vijay Anand, “Precision agriculture and farming using Internet of Things based on wireless sensor network,” Transactions on Emerging Telecommunications Technologies, 31(12), p. e3978, 2020

[7] Smarsly, K. & Law, K. H, “Coupling Wireless Sensor Networks and Autonomous Software for Integrated Soil Moisture Monitoring” in 10th International Conference on Hydroinformatics. Hamburg, Germany, 2012.

[8] G. Villarrubia, J. De Paz, D. Hernández de la Iglesia, & J. Bajo, “Combining Multi-Agent Systems and Wireless Sensor Networks for Monitoring Crop Irrigation,” Sensors, 17, p. 1775, 2017

[9] A. Veichtlbauer, M. Ortmayer & T. Heistracher, “OPC UA integration for field devices” IEEE 15th International Conference on Industrial Informatics (INDIN), Emden, Germany, pp. 419-424, 2017