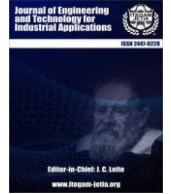




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RESEARCH ARTICLE

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INTEGRATION OF FLOW SENSORS INTO CYBER-PHYSICAL SYSTEMS FOR INTELLIGENT WATER RESOURCE MANAGEMENT IN RESIDENTIAL ENVIRONMENTS

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ABSTRACT

The growing scarcity of natural resources necessitates the development of more efficient technologies for water management in residential settings. This study introduces a solution based on Cyber-Physical Systems (CPS) for intelligent water monitoring, rooted in the RAMI 4.0 architectural model and the Asset Administration Shell (AAS) concept. The primary objective was to ensure interoperability and standardized communication between the physical and digital environments. Utilizing an experimental and quantitative methodology, a functional prototype was developed using the YF-S201B flow sensor integrated with an ESP8266 microcontroller, employing MQTT and OPC UA communication protocols. The AAS was implemented to serve as the digital representation of the asset, facilitating centralized visualization and data management. The results obtained validate the effectiveness of the proposed architecture, demonstrating accuracy in real-time monitoring of flow rates and accumulated volumes. It is concluded that applying Industry 4.0 technologies in residential contexts enables early leak detection and promotes sustainability, providing a robust and scalable solution for modern home automation.



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I. INTRODUCTION

The growing demand for sustainable water resource management has led to the adoption of advanced technologies in residential areas. Cyber-Physical Systems (CPS) integrate sensors, actuators, and control algorithms to enable intelligent automation and real-time, data-driven decision-making. In a smart home context, flow sensors connected to CPS enable continuous monitoring of water consumption, prompt leak detection, and usage optimization based on observed behavioral patterns [1].

To achieve interoperability, scalability, and compliance with Industry 4.0 principles, the integration architecture can be designed based on the RAMI 4.0 (Reference Architectural Model for Industry 4.0). This model provides a structured framework for integrating digital technologies, enabling the efficient and scalable implementation of intelligent solutions [2]. Within this framework, physical devices, such as flow sensors, are digitally represented through Asset Administration Shells (AAS). These are digital containers that encapsulate all characteristics, functionalities, and operational data of the assets.

The adoption of RAMI 4.0 and the Asset Administration Shell (AAS) in residential intelligent systems standardizes communication among devices and facilitates integration with management and analytics platforms. This integration promotes increased efficiency, security, and sustainability. This work examines the technical aspects of incorporating flow sensors into residential cyber-physical systems (CPS), highlighting how RAMI 4.0 and AAS serve as the foundation for a data-oriented and interoperable architecture [2].

II. THEORETICAL REFERENCE

Water flow measurement is crucial across various fields, including industries, treatment plants, supply systems, and academic projects. With advancements in technology, flow sensors have become more accessible, compact, and precise, enabling their application in different contexts.

One of the most widely used models is the YF-S201B water flow sensor, recognized for its simplicity and cost-effectiveness. It is commonly utilized in microcontroller-based projects and water consumption monitoring prototypes. The fundamental principle of flow measurement is based on the conservation of mass and the average fluid velocity [3].

II.1 FUNDAMENTAL PRINCIPLES OF FLOW MEASUREMENT

Volumetric flow measurement relies on the relationship between fluid velocity and the cross-sectional area of the conduit through which the fluid flows. The volumetric flow rate (Q) is defined as: $Q = vA$, where v denotes the average fluid velocity, and A represents the cross-sectional area. Thus, for a constant area, an increase in fluid velocity results in a proportional increase in flow rate. The accuracy and reliability of a flow meter are strongly influenced by installation conditions, calibration procedures, and the fluid's physical properties, such as viscosity and temperature [4]. Improper installation or inadequate calibration can significantly compromise measurement performance. Over the years, various technologies have been developed for water flow measurement, including differential pressure-based sensors, electromagnetic flow meters, ultrasonic devices, and turbine-based meters. Each technology offers specific advantages and limitations, and the selection of a particular type depends on the operational requirements and characteristics of the intended application.

II.2 TYPES OF FLOW SENSORS

II.2.1 Differential Pressure Sensors

Differential pressure sensors—such as orifice plates, Venturi tubes, and flow nozzles—measure flow rate by converting variations in pressure into quantifiable flow parameters. While these differential pressure flow meters provide a high degree of metrological accuracy, they inherently create a permanent pressure drop within the system. Additionally, their effectiveness relies on strict adherence to installation guidelines and appropriate flow conditioning to ensure measurement precision [5].

II.2.2 Electromagnetic And Ultrasonic Sensors

Electromagnetic sensors operate based on the induction of an electrical voltage when a conductive fluid traverses a magnetic field. In contrast, ultrasonic sensors utilize the propagation time of sound waves or the Doppler effect to determine the velocity of water, making them particularly suitable for non-contact measurements [6].

II.2.3 Sensor YF-S201B

The YF-S201B flow sensor is widely utilized in embedded architectures and IoT-based systems for monitoring water consumption, detecting leaks, and controlling flow. It is frequently used in experimental prototypes and cost-effective solutions, making it a practical and well-established choice in the applied literature [7], [8]. This sensor functions through a small internal turbine equipped with permanent magnets and a Hall-effect sensor. As water flows through the device, the turbine rotates, generating electrical pulses that can be interpreted by microcontrollers, including Arduino or ESP8266 platforms. Within its operational range, the relationship between pulse frequency and flow rate is approximately linear, with a frequency of 7.5 pulses per second corresponding to a flow rate of 1 liter per minute.

The sensor accommodates flow rates from 1 to 30 L/min, pressures up to 1.75 MPa, and a maximum operating temperature of 80 °C. Such sensors can be integrated into intelligent systems, serving as a foundation for estimating water consumption and implementing automated control strategies [9]. Furthermore, despite their structural simplicity, turbine-based sensors exhibit consistent performance when properly installed and calibrated [10]. In contrast, more advanced technologies, such as distributed optical fiber sensors, offer higher precision and non-invasive flow measurement capabilities, albeit at significantly greater implementation costs [11].

II.3 SOURCES OF ERROR AND CALIBRATION

As with other flow meters, the YF-S201B is susceptible to measurement errors. Factors such as air bubbles, the accumulation of debris, turbulent flow conditions, and mechanical vibrations can negatively impact measurement accuracy. Additionally, periodic calibration is essential, as variations in temperature and fluid viscosity can affect the conversion coefficient (K) [4]. A straightforward calibration procedure involves comparing the actual volume of collected water with the measured value and adjusting the conversion coefficient until both figures align. For professional applications, it is advisable to conduct calibration using traceable metrological standards and certified instrumentation to ensure measurement reliability and compliance with technical specifications [6].

Overall, the YF-S201B offers a cost-effective and efficient solution for water flow measurement in small- to medium-scale projects. Its ease of implementation and compatibility with electronic systems make it particularly well-suited for experimental research, educational purposes, and residential automation. However, for industrial applications, it is crucial to adhere to proper installation and calibration practices. Moreover, when high precision is essential, more advanced sensing technologies should be considered. The integrated use of physical sensors alongside intelligent systems is expected to play an increasingly significant role in the future of flow measurement technologies [9–11].

II.4 RESEARCH DESIGN

This study is classified as applied research, aimed at generating knowledge to address specific practical issues, primarily regarding the control and optimization of water consumption in residential settings [12]. Methodologically, the research employs a quantitative approach, prioritizing the collection and analysis of numerical data (such as flow rate and accumulated volume) to validate performance metrics and system behavior. This quantitative framework facilitates objective data classification and statistical analysis, thereby supporting the assessment of system efficiency and the reliability of measurements [13].

III. MATERIALS AND METHODS

The development of the proposed system entailed the careful selection and integration of essential hardware and software components necessary for prototype construction and experimental validation.

Hardware components:

- YF-S201B water flow sensor;
- ESP8266 microcontroller, featuring integrated Wi-Fi module.

Software tools and platforms:

- AASX Package Explorer for Asset Administration Shell modeling;
- UAExpert an OPC UA client for validation and monitoring;
- CoreTPV platform for the implementation of AAS services;
- MQTT protocol stack for data communication;
- Arduino IDE for firmware development and deployment.

This research takes an applied and experimental approach, focusing on the development and integration of flow sensors within a cyber-physical system architecture designed for intelligent water resource management in residential settings. The study combines concepts from automation, instrumentation, the Internet of Things (IoT), and sustainability, proposing a technological framework that enables intelligent monitoring of water consumption in accordance with the RAMI 4.0 reference architecture.

IV. PROTOTYPE DEVELOPMENT

At this stage, the physical prototype was systematically assembled and calibrated. This process entailed installing the flow sensor, data acquisition module, and microcontroller responsible for signal acquisition and preliminary data processing. The setup was engineered to continuously record pulses generated by the sensor, convert these pulses into both instantaneous and cumulative flow metrics, and transmit this data to the monitoring software. The architecture implemented facilitates a comprehensive data flow pipeline, spanning from the sensing layer to the application layer. This pipeline involves data acquisition, preprocessing, transmission, storage, and visualization of the measured variables.

The microcontroller performs edge-level preprocessing, including fundamental signal filtering, pulse counting, and flow metric computations, while the software layer oversees data storage, aggregation, and visualization of operational data. The integration of the physical environment—comprising measurement and acquisition devices—with the computational environment—responsible for data processing, analysis, and presentation—defines the system as a cyber-physical system (CPS). This classification is justified by the functional coupling between physical and digital components, characterized by continuous data exchange and informational feedback mechanisms. Figure 1 illustrates the assembled prototype, showcasing the placement of components, electrical interconnections, and the structural configuration adopted to support operational testing and experimental data collection.

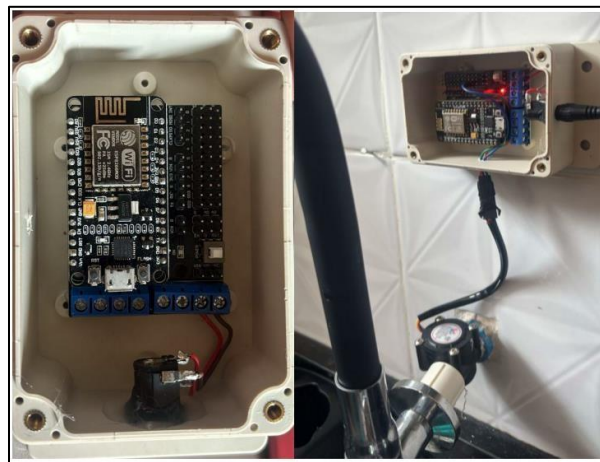


Figure 1: Assembled prototype.
Source: Authors (2026).

IV.1 FIRMWARE DEVELOPMENT

The firmware was developed using C/C++ in the Arduino IDE. Flow data is processed and converted into accumulated volume values, allowing for real-time consumption monitoring, as shown in Figure 2. A flow sensor was connected to a digital input pin that supports hardware interrupts. Pulse counting is performed through an Interrupt Service Routine (ISR), which increments a global counter with each signal transition. This method enhances the reliability of data acquisition and minimizes the risk of missing events, especially in scenarios with high pulse frequency. Additionally, the ISR logs the timestamp of the last detected pulse, enabling the system to differentiate between active and interrupted flow states. Measurement processing occurs in one-second time intervals. During each cycle, interrupts are temporarily disabled to maintain atomicity when reading the pulse counter variable, which successfully averts race conditions.

The pulse frequency is subsequently converted into an instantaneous flow rate using a firmware-defined calibration factor (pulses per liter). This value is further translated into engineering units (liters per minute) and integrated over time to compute the incremental volume, which is accumulated in the total consumption variable. The algorithm incorporates a no-flow detection mechanism based on a pulse timeout threshold of three seconds. If this threshold is exceeded, the flow rate is adjusted to zero, and the system designates the sensor as inactive. This approach enhances operational robustness and ensures data consistency. For data transmission, the communication layer employs the PubSubClient library to periodically transmit processed data to an MQTT broker.

Flow and volume values are formatted appropriately and published under designated topics, facilitating direct integration with dashboards, analytics systems, and consumption management platforms. An automatic reconnection mechanism for the broker is also implemented, which includes publishing offline and online status updates, ensuring resilience in telemetry. This processing pipeline—characterized by interrupt-driven acquisition, window-based processing, calibration through physical conversion factors, and MQTT-based publication—enables near real-time consumption monitoring while maintaining data traceability and ensuring seamless integration with the computational framework of the proposed cyber-physical system. Figure 3 illustrates the integration workflow between sensor data, the Asset Administration Shell (AAS) model, and the visualization layer.

Initially, an AAS configuration file (Type 1 shell) serves as the blueprint for the core system to instantiate an active AAS service (Type 2), defining the properties of the digital asset and its corresponding submodels in accordance with the established information structure. Once instantiated, the AAS is made accessible through standardized OPC UA nodes, allowing structured and interoperable access to its variables. An OPC UA client, such as UaExpert, can connect to the published endpoint to visualize and monitor the updated values in real time. Simultaneously, sensor data is transmitted via MQTT, and an integration module subscribes to these messages to update the corresponding properties within the AAS instance. This framework ensures that the digital model remains consistently synchronized with the physical environment, thereby enabling real-time monitoring, interoperability, and seamless interaction between the physical and digital domains.

IV.2 TYPE 1 ASSET ADMINISTRATION SHELL (AAS CONFIGURATION FILE)

Figure 4 shows the AASX Package Explorer environment, which displays an Asset Administration Shell named Hydraulic Environment AAS. This interface illustrates the structure of the digital asset, organized into submodels and elements. It allows for the visualization of the hierarchical modeling of the Asset Administration Shell.

```

1 #include <ESP8266WiFi.h>
2 #include <PubSubClient.h>
3
4 // ----- CONFIGURAÇÃO DO Wi-Fi -----
5 const char* ssid = "Familia Gama Oi Fibra";
6 const char* password = "Dob@sagem2025";
7
8 // ----- CONFIGURAÇÃO DO BROKER MQTT -----
9 const char* mqtt_server = "test.mosquitto.org";
10 const int mqtt_port = 1883;
11 const char* mqtt_client_id = "esp8266-medidor-agua";
12
13 WiFiClient espClient;
14 PubSubClient client(espClient);
15
16 // ----- TÓPICOS -----
17 const char* topic_flow = "agua/esp8266/flow";
18 const char* topic_volume = "agua/esp8266/volume";
19 const char* topic_status = "agua/esp8266/status";
20
21 // ----- SENSOR (YF-S201) -----
22 const byte SENSOR_PIN = D5; // D5 = GPIO14
23 volatile unsigned long pulseCount = 0;
24
25 unsigned long lastMillis = 0;
26 float totalLiters = 0.0;
27 unsigned long lastPulseTime = 0;
28 bool sensorAtivo = false;
29
30 // ----- CONSTANTES DO YF-S201 -----
31 const float PULSOS_POR_LITRO = 450.0; // fator de calibração típico
32 const float HZ_POR_LPM = 9.47; // Relação frequência -> vazão (L/min)
33 const unsigned long TIMEOUT_SENSOR = 3000; // ms para considerar fluxo parado
34
35
36 // ----- INTERRUPTO -----
37 void IRAM_ATTR contarPulsos() {
38   pulseCount++;
39   lastPulseTime = millis();
40 }
41 // ----- FUNÇÕES -----
42 void setup_wifi() {
43   Serial.println();
44   Serial.print("Conectando a ");
45   Serial.println(ssid);
46   WiFi.begin(ssid, password);
47   while (WiFi.status() != WL_CONNECTED) {
48     delay(500);
49     Serial.print(".");
50   }
51   Serial.println("\nWiFi conectado");
52   Serial.print("Endereço IP: ");
53   Serial.println(WiFi.localIP());
54 }
55 void reconnect() {
56   while (!client.connected()) {
57     Serial.print("Tentando conectar ao MQTT...");
58     if (client.connect(mqtt_client_id, topic_status, 1, true, "{\nstatus\":\n\"offl"));
59     Serial.println("Conectado!");
60     client.publish(topic_status, "{\nstatus\":\n\"online\"}", true);
61   } else {
62     Serial.print("Falhou, re-");
63     Serial.print(client.state());
64     Serial.println(" Tentando novamente em 5 segundos...");
65     delay(5000);
66   }
67 }
68 }
69
70 // ----- CONFIGURAÇÃO -----
71 void setup() {
72   Serial.begin(115200);
73   pinMode(SENSOR_PIN, INPUT);
74   attachInterrupt(digitalPinToInterrupt(SENSOR_PIN), contarPulsos, RISING);
75
76   setup_wifi();
77   client.setServer(mqtt_server, mqtt_port);
78
79   lastMillis = millis();
80   lastPulseTime = millis();
81 }
82
83 // ----- LOOP PRINCIPAL -----
84 void loop() {
85   if (!client.connected()) reconnect();
86   client.loop();
87
88   unsigned long agora = millis();
89
90   // Atualiza a cada 1 segundo
91   if (agora - lastMillis >= 1000) {
92     noInterrupts();
93     unsigned long pulsos = pulseCount;
94     pulseCount = 0;
95     interrupts();
96
97     float vazaoLmin = 0.0;
98     if (pulsos > 0) {
99       float hz = (float)pulsos;
100       vazaoLmin = hz / HZ_POR_LPM; // L/min
101       totalLiters += (float)pulsos / PULSOS_POR_LITRO;
102       sensorAtivo = true;
103     }
104     else if (agora - lastPulseTime > TIMEOUT_SENSOR) {
105       // sem pulsos há mais de 3 segundos = fluxo 0
106       vazaoLmin = 0.0;
107       sensorAtivo = false;
108     }
109
110     // PUBLICAR VAZÃO
111     char msg_flow[60];
112     snprintf(msg_flow, sizeof(msg_flow), "{\nvazao\": %.2f}", vazaoLmin);
113     client.publish(topic_flow, msg_flow);
114     Serial.print("flow -> "); Serial.println(msg_flow);
115
116     // PUBLICAR VOLUME
117     char msg_volume[60];
118     snprintf(msg_volume, sizeof(msg_volume), "{\nvolume\": %.3f}", totalLiters);
119     client.publish(topic_volume, msg_volume);
120     Serial.print("volume -> "); Serial.println(msg_volume);
121     lastMillis = agora;
122   }
123 }

```

Figure 2: Base Firmware Implementation.

Source: Authors (2026).

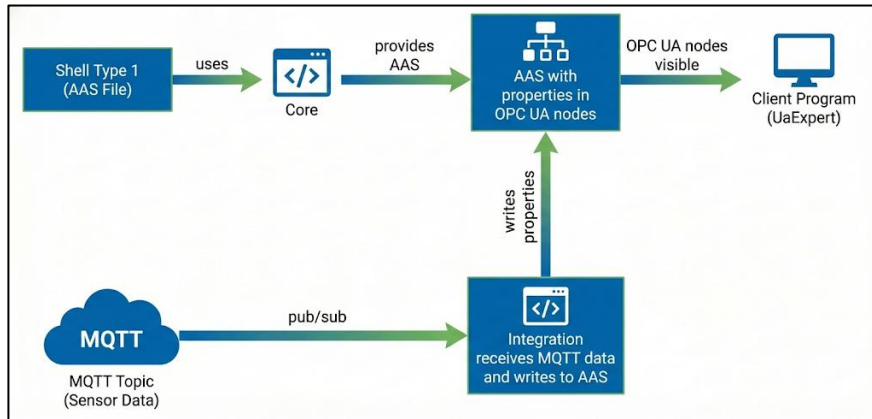


Figure 3: System Integration Flowchart.
Source: Authors (2026).

Among the displayed submodels, the Nameplate submodel consolidates asset identification information, encompassing manufacturer details, product designation, and descriptive metadata. The Hydraulic Monitoring submodel outlines operational properties such as flow rate and accumulated volume, which are essential for monitoring hydraulic system measurements. The right-hand panel presents metadata linked to the selected element, including identifiers and classification attributes. This configuration indicates that the model is designed to ensure standardized representation and interoperability, thereby facilitating integration with external services and compliance with Industry 4.0 systems. Figure 5 further illustrates the structured modeling of the AASX file, highlighting the hierarchical organization of submodels and properties within the digital asset. This representation shows how operational parameters, identification data, and monitoring variables are formally organized, ensuring semantic consistency and interoperability in alignment with the RAMI 4.0 information layer principles.

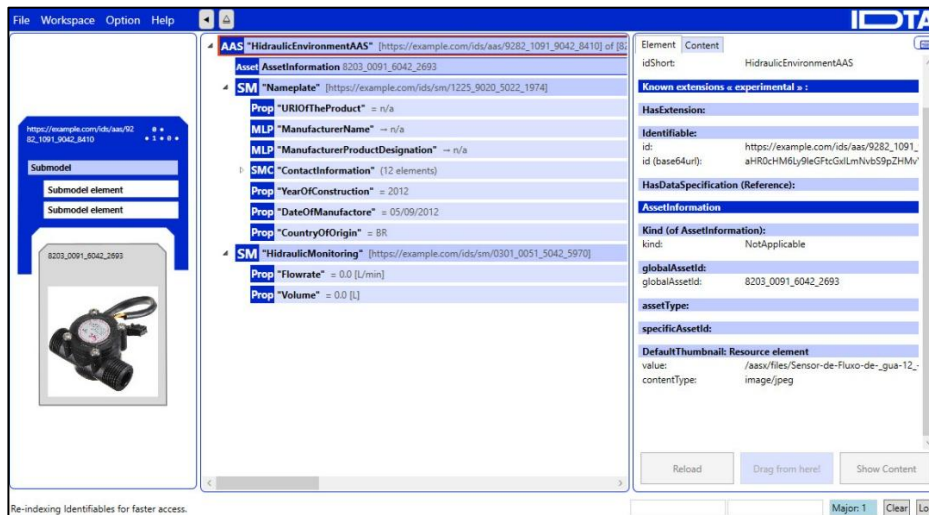


Figure 4: Developed AASX Model.
Source: Authors (2026).



Figura 5: Modelagem do AASX.
Source: Authors (2026).

IV.3 CORE (TYPE 2 AAS SERVICE)

The CORE module is tasked with the instantiation and hosting of the Asset Administration Shell (AAS) as defined in the Type 1 configuration file. It converts the static AAS model into a dynamic service that can communicate through HTTP and OPC UA protocols. Once deployed, this service makes the AAS accessible over the network, presenting its properties as organized OPC UA nodes.

IV.4 MQTT INTEGRATION

An MQTT broker continuously disseminates data from physical sensors (such as voltage, flow rate, and temperature). An integration module subscribes to these messages, updating the relevant properties within the AAS instance to ensure consistency between the physical environment and its digital counterpart. This synchronization mechanism guarantees that the OPC UA nodes consistently reflect the most current sensor values.

IV.5 AAS PROPERTIES EXPOSED AS OPC UA NODES

The AAS hosted by the CORE exposes its properties as standardized OPC UA nodes, ensuring compatibility with any OPC UA client. This facilitates interoperability with SCADA systems, MES, and industrial monitoring software.

IV.6 CLIENT APPLICATION (UAEXPERT)

UAExpert, functioning as an OPC UA client, connects to the endpoint provided by the CORE service. This connection enables real-time visualization, inspection, and monitoring of the AAS properties, acting as a validation layer for the entire integration workflow.

Figure 6 illustrates a schematic representation of the integration of flow sensors within a cyber-physical system architecture, designed for intelligent water resource management in residential environments. This model is organized according to the RAMI 4.0 (Reference Architectural Model for Industry 4.0), which categorizes intelligent industrial systems across hierarchical, functional, and lifecycle dimensions.

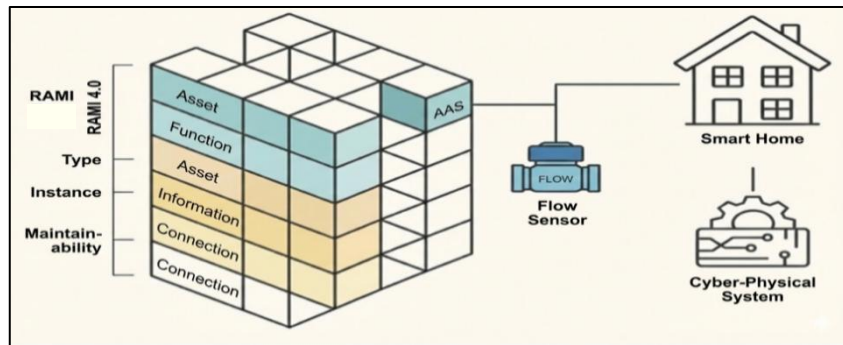


Figure 6: Flow Sensor Integration within a Cyber — Physical System.
Source: Authors (2026).

In the proposed architecture, the flow sensor acts as the physical asset responsible for collecting data from the real world, aligning with the Asset layer of the model. The gathered measurements are transformed into digital information and transmitted through the Communication and Information layers, thereby establishing the interface between the physical and digital realms. The cyber-physical system functions at the upper layers of the model, engaging in data processing, storage, and analytical tasks. Through this transformation, raw measurements are converted into actionable insights that facilitate automated decision-making. The system may perform control actions, such as valve actuation or issuing alerts for excessive consumption, thereby ensuring ongoing integration with the smart residential environment.

Additionally, the model underscores the concept of the Asset Administration Shell (AAS), which acts as the digital counterpart of the physical asset—in this case, the flow sensor. The AAS enables standardized identification, configuration, and lifecycle management of the asset within an automation network. Overall, this diagram illustrates the modular and interoperable structure proposed by Industry 4.0, showcasing how the integration of physical sensors, digital communication, and intelligent processing can enable efficient monitoring of water consumption in residential settings. By emphasizing the significance of connectivity and standardization, the model presented serves as a conceptual reference for the development of sustainable and intelligent home automation systems.

V. RESULTS AND DISCUSSIONS

V.1 FLOW RATE

An analysis of the instantaneous flow rate was performed to evaluate the performance of the proposed architecture regarding data acquisition, transmission, and its availability from the physical environment to the digital domain. Beyond merely assessing measurement accuracy, this evaluation aimed to confirm how sensor-generated data are integrated into the digital model and disseminated across the RAMI 4.0 layers. The specific objective was to validate the integrity and continuity of the data pipeline, which spans from sensing and edge-level processing to communication, AAS updating, and OPC UA exposure. This ensures that the measured variables can be effectively utilized by higher-level services and applications within the cyber-physical system framework. Figure 7 delineates the temporal dynamics of the instantaneous flow rate observed during the operational phase of the system.

The fluctuations noted throughout the specified period are indicative of varying residential water consumption patterns, which are characterized by brief usage events punctuated by intervals of relative inactivity.

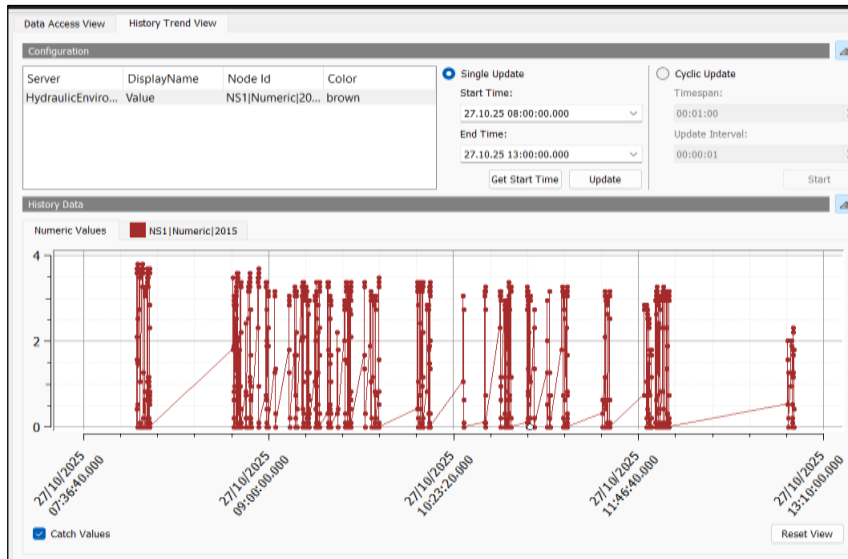


Figure 7: Instantaneous Flow Rate Results Displayed by the Monitoring System. Source: Authors (2026).

The results indicate that these variations were effectively captured at the physical sensing layer and consistently transmitted to the digital environment. The synchronization of acquisition, processing, and data publication ensured that the digital representation accurately reflected the real-time process conditions. This consistency affirms the reliability of the proposed integration architecture and validates the continuity of the data pipeline across the RAMI 4.0 layers. As a result, the instantaneous flow rate is established as a reusable process variable, capable of supporting real-time monitoring applications, anomaly detection mechanisms, and automated control strategies within the framework of cyber-physical systems.

V.2 ACCUMULATED VOLUME

The assessment of accumulated volume enhances the analysis of instantaneous flow rates by offering a broader temporal perspective on water consumption behavior. This metric is derived from the continuous integration of instantaneous flow measurements, providing a consolidated overview of water usage over time. Such an overview is particularly valuable for management applications, historical analyses, and decision-support processes. Figure 8 depicts the temporal evolution of accumulated volume, highlighting a progressive increase corresponding to the consumption events identified in the flow rate analysis.

The profile of the curve affirms the internal consistency between instantaneous measurements and system-level processing, as volume increments occur solely during active flow intervals. The variations in the slope of the accumulated volume curve indicate differences in consumption intensity, demonstrating that the aggregation and storage mechanisms operated effectively within the digital environment. As a result, accumulated volume evolves from a locally computed variable into a persistent and structured informational asset within the cyber-physical system. This transition paves the way for advanced applications, including water efficiency assessment, identification of usage patterns, and the development of automated decision-making strategies.

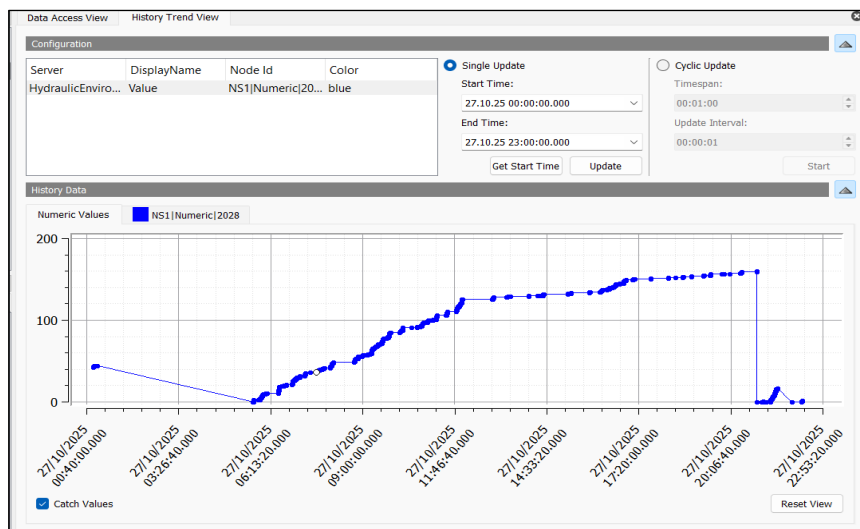


Figure 8: Accumulated Volume Results Displayed by the Monitoring Application. Source: Authors (2026).

V.3 FLOW RATE AND ACCUMULATED VOLUME

The integrated analysis of flow rate and accumulated volume provides a comprehensive evaluation of overall system coherence, accounting for both instantaneous behavior and the cumulative impact of consumption over time. This combined assessment is crucial for validating the logical consistency of the processed data and the effectiveness of the integration between the physical and digital domains within the proposed architecture. Figure 9 illustrates the simultaneous visualization of instantaneous flow rate and accumulated volume recorded during system operation. This combined representation clearly depicts the direct relationship between consumption events and the progressive increase in accumulated volume, reinforcing the physical and mathematical integrity of the processed measurements.

Each significant fluctuation in flow rate corresponds proportionally to increases in accumulated volume, affirming the effective coordination among data acquisition, signal processing, and digital model updating mechanisms. This temporal consistency indicates that the system maintains alignment across various abstraction layers, as outlined by the RAMI 4.0 framework. The integrated results enhance the reliability of the proposed architecture and underscore its potential for advancing intelligent water resource management applications. By providing structured, interoperable access to both real-time and historical data, the system facilitates more sophisticated analytical models and automated decision-making strategies within smart residential environments.

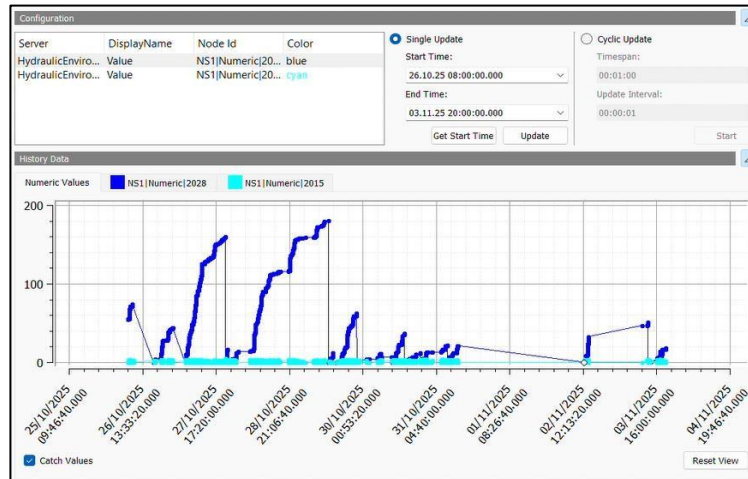


Figure 9: Combined Flow Rate and Accumulated Volume Results Displayed by the Monitoring System.

Source: Authors (2026).

VI. CONCLUSIONS

The integration of flow sensors into cyber-physical systems marks a significant advancement in the intelligent management of water resources within smart residential settings. This approach facilitates real-time monitoring, early leak detection, and optimization of consumption, ultimately enhancing resource efficiency and sustainability. By adopting the RAMI 4.0 reference model alongside the Asset Administration Shell (AAS) concept, the proposed architecture ensures both standardization and interoperability between physical devices and digital services.

The implementation of communication protocols such as OPC UA (IEC 62541) [14] and MQTT enables secure and scalable data exchange, thereby supporting service-oriented architectures and paving the way for advanced applications, including Digital Twins and predictive maintenance strategies. In summary, the proposed integration framework illustrates the practical application of Industry 4.0 principles beyond traditional industrial boundaries, extending their benefits to residential environments. This contribution underscores the importance of digital transformation in fostering energy and water efficiency, in line with the guidelines set forth by Plattform Industrie 4.0 [15] and the IEC 63278 standard [16].

VII. AUTHOR'S CONTRIBUTION

Conceptualization: Roberto Higinio Pereira da Silva.

Methodology: Roberto Higinio Pereira da Silva.

Investigation: Roberto Higinio Pereira da Silva.

Discussion of results: Roberto Higinio Pereira da Silva.

Writing – Original Draft: Roberto Higinio Pereira da Silva.

Writing – Review and Editing: Daniel Carlos de Almeida Mendonça.

Resources: Daniel Carlos de Almeida Mendonça.

Supervision: Roberto Higinio Pereira da Silva e Daniel Carlos de Almeida Mendonça.

Approval of the final text: Roberto Higinio Pereira da Silva e Daniel Carlos de Almeida Mendonça.

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IX. REFERENCES

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