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Development of a telemetric monitoring system for water pipeline supply

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Abstract*– In the face of the pressing water crisis affecting communities, an intelligent telemetric system is presented for monitoring, control, and fault detection in drinking water supply systems. This system integrates solenoid valves, water flow sensors, and water meters to efficiently manage real-time data within the pipeline. Teltonika RUT955 cellular routers were integrated for control, data transmission, and reception at designated points. Modbus was incorporated as a data conversion agent between the sensors and the router system. Subsequently, data is communicated via the MQTT protocol to a broker, where it is processed using JavaScript algorithms. Finally, the data is visualized on a dashboard with line charts, gauge charts, tables, and maps, facilitating further analysis. The project operates on solar energy for field devices, with consumption not exceeding 12 volts per device. This approach considers the critical nature of data loss and the limited access to public energy supply available underground in communities. The simplified, precise, and versatile visualization interface was implemented using HTML in conjunction with CSS. Users have tools such as report generation and local data storage, all updated in real time. By identifying connection points for each device, sensors are visualized on a map, tracing their flow trajectory, calculating distances between pairs, and generating flow level states for each point.

Keywords-- IoT, M2M, MQTT, Cellular Router, Modbus..

I. INTRODUCTION

Rural communities, traditionally vulnerable to scarcity and poor quality drinking water, are embracing technological innovation to transform water management. The integration of sensors and Internet of Things (IoT) devices into supply systems is revolutionizing the management of this critical resource. These advances drive efficiency through real-time monitoring of consumption, leak detection and distribution optimization. They promote sustainability by reducing waste and encouraging responsible consumption practices. They strengthen resilience to weather events or infrastructure failures through early warnings and timely responses. However, the success of these solutions lies in a holistic approach that includes community empowerment and participation, sustainable financing mechanisms and an appropriate regulatory framework. Ultimately, the adoption of technologies such as sensors and IoT in water management in rural communities marks a milestone towards a more sustainable and resilient future, where equitable access to this vital resource is no longer a dream but a palpable reality.

II. THEORETICAL FRAMEWORK

The proposed system on [1] which consists of a network of ZigBee wireless sensors installed along the supply pipe. These sensors collect data on pressure, flow and water quality in real time. The collected data are transmitted wirelessly to a central node using ZigBee technology, which is characterized by low power consumption and wide coverage.

PIPENET [2] is an innovative proposal for remote and real-time monitoring of water pipelines, especially in rural or hard-to-reach areas. This wireless sensor network is based on ZigBee technology, known for its low power consumption and wide coverage, and is designed to detect leaks, monitor water pressure and flow, and provide accurate information on pipeline status. PIPENET network nodes are composed of sensors integrated into compact and rugged devices, capable of operating autonomously for long periods thanks to long-life batteries.

For water supply monitoring [3] where his innovative approach is based on the integration of state-of-the-art technologies such as the Internet of Things (IoT), cloud computing and data analysis, with the objective of optimizing water management in rural and urban communities. Pipe Sense is characterized by its flexibility and scalability, allowing its adaptation to different types of water distribution networks, from small to complex systems. Pipe Sense's modular architecture facilitates the incorporation of new sensors and devices, as well as integration with existing water management systems. Rural communities around the world face serious challenges in accessing safe drinking water in an equitable and sustainable manner. Traditional water supply systems, often rigid and inflexible, are plagued by leakage, inefficient consumption, and a lack of capacity to adapt to changing demands [4]. This situation not only compromises the health and well-being of communities, but also limits their socioeconomic development. In this context, emerging technologies offer promising solutions to optimize water management in rural communities[5]. The telemetric monitoring system for water supply systems is fundamental for the management, a correct design is essential as you can see in the Figure 1.

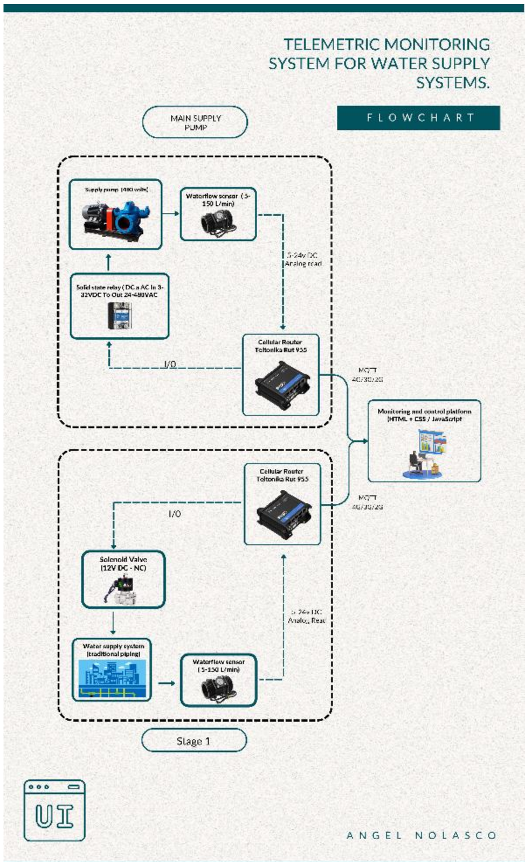

Fig. 1 Concept of design

Declarative processes, for example, enable more flexible and adaptive management of supply systems, while smart monitoring through sensors and devices connected to the Internet of Things (IoT) allows for real-time leak detection, optimized pump control, and accurate monitoring of water consumption[6]. The implementation of IoT-controlled supply pumps represents a significant advance in the efficiency and sustainability of water management. These pumps, automatically adjusted based on actual demand, reduce energy and water waste, minimize environmental impact, and ensure a more equitable supply for the community [7].

The Internet of Things (IoT) is revolutionizing the way water is managed in rural communities. This network of smart devices, sensors and actuators connected to the internet allows real-time data on water supply to be collected and analyzed, providing valuable information to optimize the efficiency, sustainability and resilience of systems [8]. Water flow sensors, for example, enable accurate and timely leak detection, minimizing water waste and associated costs. IoT-controlled solenoid valves regulate water flow efficiently, reducing unnecessary consumption and optimizing resource allocation [9]. Smart water meters, integrated to the IoT network, provide accurate data on individual and community consumption, allowing to identify usage patterns and promote responsible consumption practices. The integration of these IoT technologies into rural water supply systems not only improves efficiency and sustainability, but also strengthens the ability of communities to manage this vital resource responsibly and equitably [10].

Effective water management in rural communities requires a holistic approach that combines IoT technologies with other complementary solutions. Cellular networks, for example, provide the necessary communication infrastructure for real-time data transmission from IoT devices to monitoring and control platforms [11]. Communication protocols such as MQTT and Modbus ensure interoperability between different IoT devices, enabling seamless and efficient communication within the water management ecosystem [12].

Web-based data dashboards visualize the information collected by sensors and IoT devices, enabling water managers to make informed and timely decisions [13]. The development of efficient IoT applications for water management relies on tools such as Node.js, HTML and CSS [14]. These tools enable the creation of intuitive and easy-to-use interfaces for data visualization and analysis, as well as for the control and configuration of IoT devices[15]. Together, the adoption of these complementary technologies together with IoT solutions allows the establishment of a comprehensive water management system in rural communities, promoting an efficient, sustainable, and resilient use of this vital resource. In order to better understand the overall water management system, it is essential to seek information on the constraints identified by other authors, such as those shown in Table 1.

TABLE I
AUTHOR LIMITATIONS

No.	Article	Author	Author's limitations
1	*Remote Monitoring System of Water Supply Pipeline Based on ZigBee and Wi-Fi*	*(Tie et al., 2018)*	Zigbee and WiFi communication technologies are area-restricted, which shortens their communication ranges.
2	*PIPENET, A Wireless Sensor Network for*	*(Stoianov et al., 2007)*	Precise time synchronization, power management and effective use of bandwidth are the

	Pipeline Monitoring		consequences of such a robust system.
3	*PipeSense: A framework architecture for in-pipe water monitoring system*	*(Nasir & Soong, 2009)*	Reliance on RFID technology for data collection
4	*A Wireless Sensor Network Based Pipeline Monitoring System*	*(Anupam a et al., 2014)*	The system requires a high bandwidth communication protocol to move large amounts of data.
5	*Water Pipeline Monitoring System Using Vibration Sensor*	*(M. I. M. Ismail et al., 2014)*	The system may have difficulties in detecting leaks in pipes under certain water pressures, due to the results shown, they mention that the vibration signals are similar for leaking and normal pipes at water pressures of 0.8 and 1.0 kgf/cm².

III. METHODOLOGY

The project allows addressing the complexities of the project in a comprehensive manner, graphically manipulating data obtained from the pipes through sensors, combining the rigor of the quantitative methodology in which it is estimated to make use of information provided by the authorities, obtained in case studies, thus adjusting the exact position of the devices for an efficient flow of water in identified sectors where control points are required, providing a solid and efficient basis adapting to the needs of the community.

A. Tools and Instruments

1. Visual Studio Code: Programming environment for Python, JavaScript, HTML, CSS, and C++. Allows debugging and testing of code.
2. HTML: Structure and presentation of information in the graphical interface.
3. CSS: Adaptation of the interface to a clear and organized presentation.
4. JavaScript: Interactive interface to manage actions on the data dashboard. Allows remote control of solenoid valves and data conversion to graphics.
5. Node.js: Data management and interaction with IoT devices. Platform for constant real-time information management.
6. Mqtt.js: Communication between user and field devices. Data exchange to a central server.
7. Plotly.js: Attractive and understandable presentation of information through dynamic and customizable graphics.
8. Teltonika RUT955 router graphical configuration interface: Configuration of network parameters for redundant connection to the cellular network. Allows the router to act as a data gateway.
9. Modbus TCP/IP: Communication protocol between machines for the flow of information from electrical pulses and electrical current measurements. Transfers data converted into measurable numerical figures.

B. Materials

The materials that make up the IoT ecosystem have the required data flow capacity, relevance of use and adaptability to the system under development. These are:

- Teltonika Rut955 router set.
- Water flow sensor.
- Solenoid valve
- DC/AC relay
- Ethernet cable
- 12-volt battery
- Charge controller
- Solar panel
- Flexible PVC pipe coupling
- Solid #16 electrical cable

C. Study methodology

1. System desing:

The system is composed of three levels: system design, implementation, and production.

- In system design the tools are integrated, the platform is defined (graphics, styles).
- The IoT gateway is prototyped (equipment, router, server) and the data acquisition units (sensors and actuators) are selected.

2. Implementation:

At this level, the prototypes are integrated, and the development interfaces are worked on.

- The data visualization platform is developed (HTML, CSS, JavaScript).
- The network architecture is configured (MQTT broker in the cloud, access, permissions, MQTT.js configuration).
- Serial communication with sensors and actuators is established (internal Modbus TCP server in the router).

3. Production as a whole:

At this level the systems are already communicating information with the deployed devices.

- Changes are executed in real time on the data board.

- Anomalies detected in the pipeline are presented and the remote drive is controlled.
- To implement a good water supply management system is important define a good Hierarchical Implementation Methodology as shown in Figure 2.

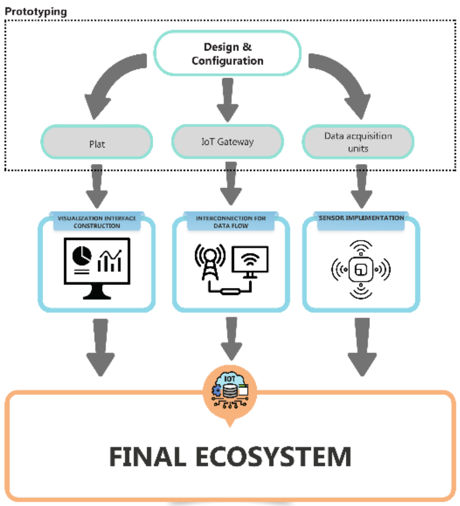

Fig. 2 Hierarchical Implementation Methodology

D. *Validation Methodology*

An analysis of the data collected during the implementation of the system is performed to evaluate the effectiveness of the system in solving the identified problems. Appropriate statistical tests are used to determine whether the differences observed between the values before and after system implementation are statistically significant. Together, the data obtained are compared with statistical data established by other indicators, such as consumption and failure data recorded by the local organization, allowing to contextualize the results of the project and to evaluate its impact broadly.

IV. RESULTS AND ANALYSIS

The results of the overall system development are presented, detailing the operating principles of the platform, its final model and the integration of the database, which connects directly with the field devices remotely.

A. *MQTT broker Implementation*

A server/Broker is created in the cloud that provides services from Amazon Web Services (AWS) through the EMQX portal dedicated to the MQTT implementation; a solid solution in terms of quality of service, allowing connectivity 24 hours a day from anywhere in the world without interruptions, due to the continuous backup of the data required in the project. The accesses are configured with user and password authentication, both for the subscriber and the publisher, and the incoming connections are monitored in the sessions created when a user accesses the topics to which he subscribes. Also, the default ports shown are intended for the different origins of the users; 1883 for devices and WebSocket 8083 for applications respectively. A visual example of the MQTT broker implementation is shown in Figure 3.

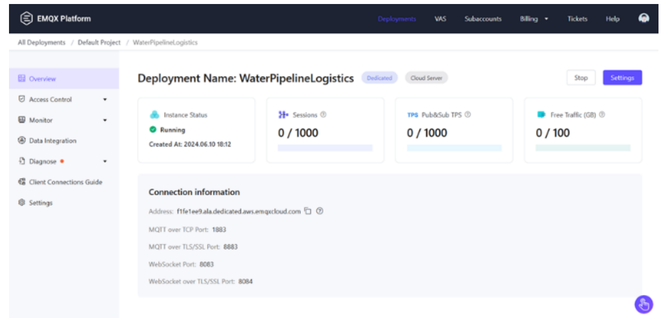

Fig. 3 MQTT Broker in the cloud from EMQX via AWS

B. *Data Dashboard Development*

The data dashboard is complex when trying to integrate certain functionalities that the project entails, it is implemented under the Node.js runtime environment that integrates the express.js framework encompassing the MQTT library which streamlines the way in which the data is worked together, making JavaScript adaptable with HTML in embedded JavaScript templates (.ejs) facilitating execution and deployment in vercel. The Visual Studio project structure as shown in Figure 4.

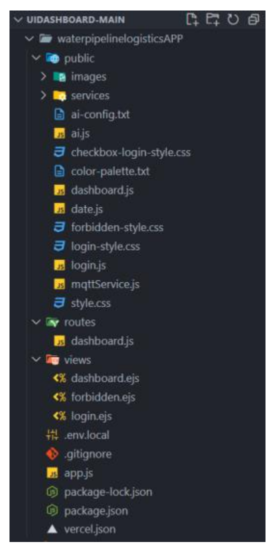

Fig. 4 Visual studio project structure

The files are distributed according to their functions, where the main one in which the base/structure of the web page is mounted is dashboard.ejs in which the data is embedded to HTML from JavaScript (JS) improving and facilitating the incorporation of variables in main code and using them in different algorithms that JS supports.

The default separation created in express.js maintains and debugs the code better, adjusting some library functions in Mqttservice.js and allows the necessary code adjustment in cases where the server or connection fixes impact the execution negatively and some further reconditioning is needed.

Relevant data is displayed from the platform and status information is updated periodically as changes arise within the communication space between the platform and the router. The current connection status is also reported directly on the platform. From the browser console in question, each event can be identified in detail for future reference of any required changes. A better representation can be seen in the Figure 5.

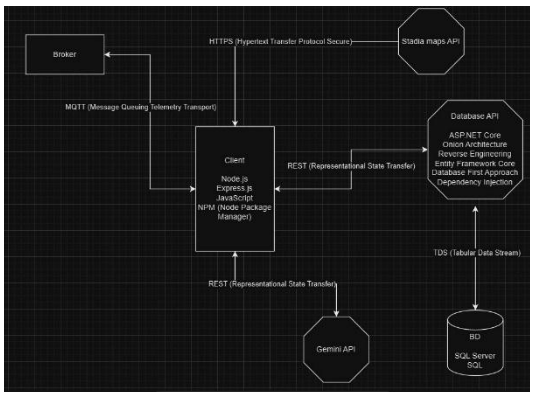

Fig. 5 Schematic structure of the tools that make up a web application

Messages to and from the platform are in plain text format, the request response code is broken down to obtain the pure information which is then graphed and stored for display and future reference. The request format from the platform is structured as follows: 0 <COOKIE> <IP_TYPE> <IP> <PORT> <TIMEOUT> <SERVER_ID> <MODBUS_FUNCTION> <FIRST_REGISTER> <REGISTER_COUNT/VALUES> requesting from the Modbus server in the router the information and type of data it expects in the form of a response.

C. Results

The results in the section demonstrate full functionality, detecting faults remotely with short response latency and intervals that safeguard the effectiveness of system detection, monitoring and control. The project data dashboard can be seen in the Figure 6.

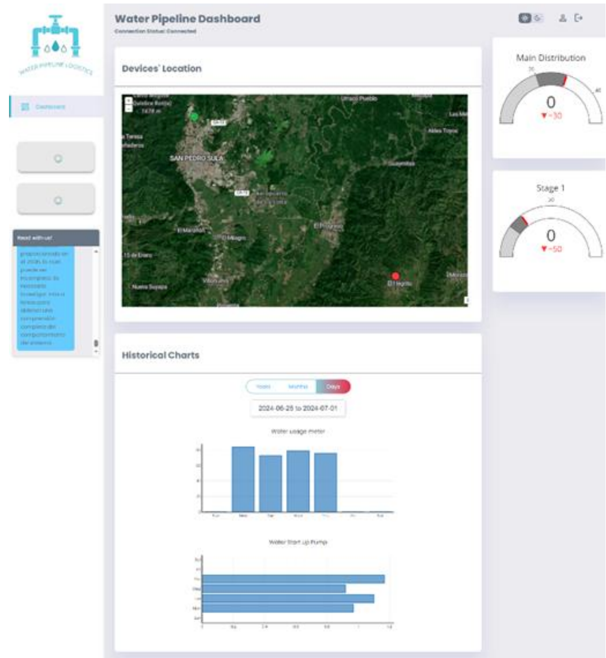

Fig. 6 Project Data Dashboard

As stated, the data depends on the 4G mobile network of the TIGO operator to be transmitted to the website, however, the network is susceptible to communication failures due to weather conditions where losses do not greatly alter the results, so the requests that reach the router are repeated in a constant cycle of every 500 milliseconds for the data since the remote on/off controls of the water pump and solenoid valve receive status confirmation from the controller, which does not represent a risk in the constant communication. During the online execution of the server, a percentage of no more than 4% error in the requests was identified, which was worked relating the maximum accuracy that can be had by making the most requests for the sensor reading without losing it due to the mobile connection, so that the number of readings that can be had is proportional to the data losses that are averaged for the calculation of water pressure, 500 ms were sufficient to obtain 120 samples that are averaged per minute to determine in what proportion is the water flow in both sensors.

The gain of the router antenna allows a high fidelity to the mobile connection; however, the coverage area of the mobile network depends on a lot so that there are no lapses in which the communication is saturated and considering the losses in the samples in highly adverse conditions, a high accuracy of the data is achieved. The measurement of the sensor from the MQTT request can be seen in the Figure 7.

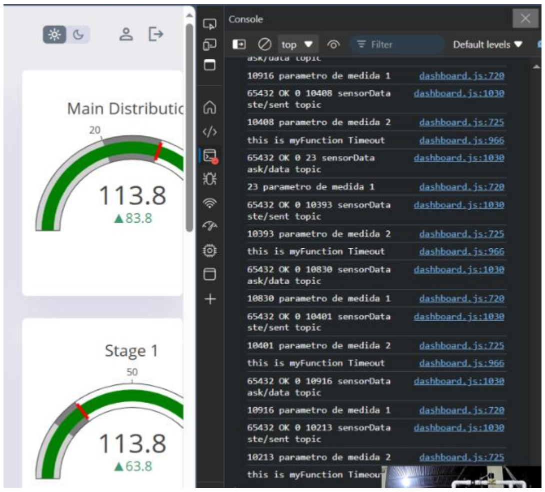

Fig. 7 Sensor reading from MQTT requests in the web application displayed on console

V. CONCLUSIONS AND RECOMMENDATIONS

- The developed system responds efficiently to events occurring within the router with an approximate latency of 10 microseconds. Flow rate estimation is performed by comparing the pressure differences between two flow sensors located in designated sectors, allowing for precise control of pipe status.
- Integrating the platform into an institution's own domain offers significant advantages, including low resource consumption and the ability to scale the platform to connect more devices in the future.

It is recommended to maintain the use of equipment that integrates support for both analog and digital signals to ensure versatility in signal processing. While practical, the implementation of modules such as the ESP32 should be limited to small-scale applications, as their use may constrain the network's scalability and data throughput. For professional and institutional environments, it is advisable to adopt robust, custom-developed platforms tailored to the specific needs of the system. Standardized solutions like ThingSpeak, although popular, should be avoided when their functionality does not fully align with the project's technical requirements.

Moreover, the continued use of multifunctional, task-specific sensors is encouraged, as this approach enhances system efficiency by reducing hardware redundancy. Emphasis should also be placed on strengthening remote operation capabilities, ensuring they are equipped with secure communication protocols and reliable control mechanisms. This strategy is particularly beneficial for institutions managing critical infrastructure, such as pipelines, where operational reliability and real-time responsiveness are essential. Adopting these recommendations may lead to a significant improvement in workflow efficiency and long-term sustainability.

A. Applicability

The system focuses on modernizing water management in the pipes that distribute water to homes, however, the system applies to irrigation and fish farming systems for the water management they require, as it helps streamlining remote response processes without suffering any delay in daily tasks and unnecessary resource expenses that are easily addressed from the platform, giving a better service and water flow through the pipes.

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