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Web based IoT monitoring system for ultrasonic water flow measurement using ESP32-S3 and cloud database

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ABSTRACT

Efficient water management is crucial for ensuring sustainable resource utilization and reducing water losses in both industrial and domestic applications. This study presents the design and implementation of a smart water monitoring system based on an ultrasonic flow meter, which enables accurate, real-time measurement of water flow without physical contact with the medium. The proposed system integrates ultrasonic sensors with a microcontroller-based data acquisition unit and wireless communication to transmit flow rate, volume, and consumption data to a cloud-based monitoring platform. The system was tested in various flow conditions to evaluate accuracy, stability, and energy efficiency. Experimental results demonstrate that the ultrasonic flow meter achieved a measurement accuracy of ±1% compared to a reference turbine flow meter, while maintaining minimal power consumption. Furthermore, the integration of Internet of Things (IoT) capabilities allows remote monitoring, anomaly detection, and data logging for long-term analysis. The results indicate that this ultrasonic-based monitoring system provides a reliable and non-invasive solution for smart water management, offering potential applications in household metering, agricultural irrigation, and industrial fluid monitoring.

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1. INTRODUCTION

Water is a vital natural resource for human survival, economic advancement, and ecological sustainability [1]. Accelerated urbanization, population increase, and industrial growth have significantly intensified water demand, leading to challenges in water distribution and management [2]. The World Bank indicates that over 30% of treated water is wasted due to leakage, inaccurate metering, and inadequate monitoring systems, particularly in developing regions [3]. Thus, an efficient and accurate water monitoring system is essential for assuring optimal use, minimizing waste, and fostering sustainable water resource management [4]. The integration of advanced technologies, such as the Internet of Things (IoT), embedded systems, and intelligent sensors, has generated new prospects for real-time water monitoring and data-driven decision-making.

Conventional water flow measuring methods, such as mechanical or turbine flow meters, frequently exhibit disadvantages including degradation, pressure loss, and restricted measurement precision, particularly under fluctuating flow circumstances [5]. These traditional methods necessitate direct interaction with the fluid, so elevating the danger of contamination and diminishing the sensor's longevity [6]. Conversely, ultrasonic flow meters provide a non-invasive method, employing the time of flight or Doppler principle to ascertain flow velocity by identifying fluctuations in ultrasonic signal transmission [7]. Their contactless characteristics, high accuracy, and versatility with various pipe materials render them an appealing choice for contemporary water monitoring applications [8].

A recent study investigated the incorporation of ultrasonic flow meters with IoT-based platforms to improve the efficiency and scalability of water management systems [9]. Real-time data can be transferred to centralized servers or cloud databases for analysis and visualization via wireless communication technologies like as Wi-Fi, LoRa, or GSM [10]. This connection facilitates the rapid identification of anomalies, including leakages, excessive consumption, or system failures. The utilization of cost-effective microcontrollers such as Arduino, ESP32, or Raspberry Pi facilitates the development of economical yet high-performance monitoring solutions appropriate for both residential and industrial applications [11].

This study examines the design and implementation of an IoT-enabled water monitoring system utilizing an ultrasonic flow meter as the principal sensor component [12]. The system seeks to deliver precise flow rate and volume measurements, instantaneous data transmission, and intuitive display via a cloud-based interface [13]. Experimental assessments were performed to ascertain the system's precision, stability, and efficiency across various flow conditions [14]. The findings indicate that the proposed design is a dependable, low-maintenance, and scalable solution for intelligent water management, facilitating future advancements in smart city infrastructure and sustainable resource consumption [15].

2. METHOD

The methodology used in this study focuses on designing and implementing a smart water monitoring system that includes an Ultrasonic Flow Meter, an ESP32-S3 microcontroller, an InfluxDB time-series database, and a Next.js web-based dashboard. The system was designed to provide precise, real-time, and scalable water flow monitoring in both residential and industrial environments [16] [17]. The overall workflow consists of three major stages: hardware design, software design, and database integration, each described in the following subsections.

Hardware Design

The hardware design consists of three main components: the Ultrasonic Flow Meter sensor, the ESP32-S3 microcontroller, and the power and communication modules. Figure 1 shows the schematic wiring diagram of the water monitoring system using ESP32-S3.

Figure 1. Schematic wiring diagram

The Ultrasonic Flow Meter operates using the time-of-flight (ToF) principle. Two ultrasonic transducers are mounted at a fixed distance along a water pipe, one acting as a transmitter and the other as a receiver. When water flows, the time difference between the upstream (t_{up}) and downsteam (t_{down}) signals is measured. The flow velocity v is computed as:

$$v = \frac{L}{2cos\theta} \times \frac{t_{up} - t_{down}}{t_{up} \times t_{down}} \quad (1)$$

Where L is the distance between transducers and θ\thetaθ is the inclination angle of the ultrasonic beam. The **flow rate (Q)** is then calculated as Q=A×v, where A is the cross-sectional area of the pipe. The **ESP32-S3** microcontroller serves as the central processing unit responsible for data acquisition, signal processing, and communication. The microcontroller receives the timing signals from the ultrasonic sensor through digital input pins, performs flow rate calculations, and sends the results to the InfluxDB server over a Wi-Fi network [18]. A voltage regulator and power supply (5V/3.3V DC) ensure stable operation of all electronic components. Figure 2 shows the installation of the ultrasonic sensor.

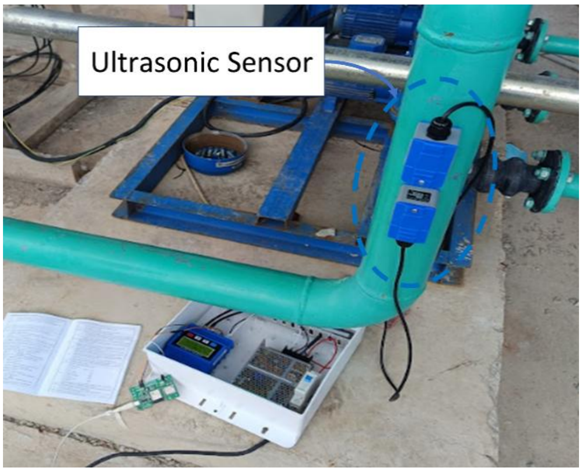

Figure 2. Ultrasonic sensor installation

Software Design

The software design is divided into two layers: embedded firmware and web-based interface. The firmware running on the ESP32-S3 was developed using Arduino IDE and programmed in C++. It performs key operations including data acquisition, time measurement, flow rate computation, and communication. The firmware reads the ultrasonic sensor output, filters noise using an averaging algorithm, and periodically transmits the processed data to the InfluxDB database through MQTT protocol [19] [20]. The software is optimized for minimal latency and energy consumption, ensuring reliable real-time performance even under continuous operation. Figure 3 shows the sensor configuration code and MQTT communication in Arduino.

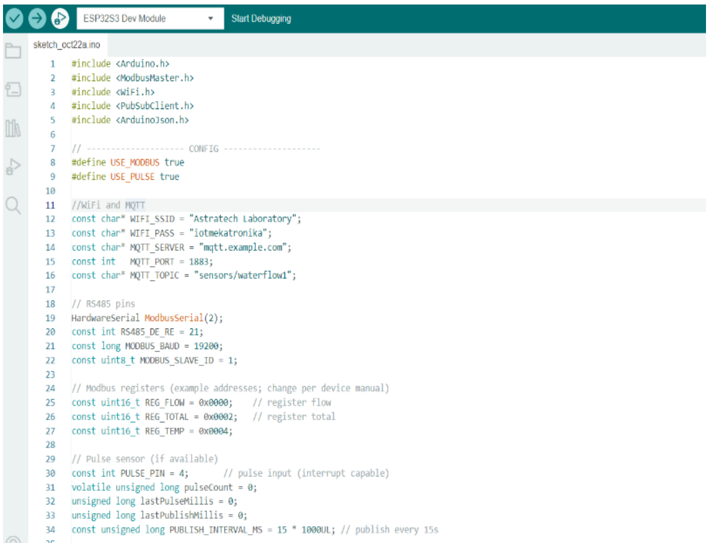

Figure 3. Arduino Program for Communication Sensor and ESP32S3

The web interface was developed using Next.js, a React-based framework optimized for server-side rendering and high-performance front-end visualization. The website communicates with the InfluxDB backend using a RESTful API, fetching the latest data in JSON format. The dashboard displays live and historical water flow data in graphical form (using Chart.js or Recharts), showing flow rate trends, cumulative volume, and usage statistics. The interface also includes an alert system that notifies users when abnormal flow conditions occur, such as leakages or sudden drops in flow rate [21]. This enhances the system's usability for real-time monitoring and decision-making [22]. Figure 4 is the API code for NextJS communication with InfluxDB.

```
app > api > water-data > latest > JS route.js > GET > data > <function>
// app/api/water-data/latest/route.js
import { queryApi } from '../../../../lib/influxdb'
import { NextResponse } from 'next/server'

export async function GET() {
  try {
    const fluxQuery = `
      from(bucket: "${process.env.INFLUXDB_BUCKET}")
        |> range(start: -1h)
        |> filter(fn: (r) => r._measurement == "water_data")
        |> last()
    `

    const data = await new Promise((resolve, reject) => {
      const result = {}

      queryApi.queryRows(fluxQuery, {
        next(row, tableMeta) {
          const obj = tableMeta.toObject(row)
          if (obj._field && obj._value !== undefined) {
            result[obj._field] = obj._value
          }
        },
        error(error) {
          reject(error)
        },
        complete() {
          resolve(result)
        },
      })
    })
```

Figure 4. NextJS API Interface with InfluxDB

Database Design

The system employs InfluxDB, an open-source time-series database, as the primary data storage platform. InfluxDB was selected because it is optimized for handling temporal data data indexed by time which is ideal for IoT sensor readings that are generated continuously [23]. The database architecture is based on a bucket model, where each measurement, such as flow rate, total volume, and timestamp is stored as a time-series entry. Data are transmitted from the ESP32-S3 to InfluxDB using the HTTP API with JSON payloads containing the measurement data and timestamps. Figure 5 shows a sample programming code for the InfluxDB Database.

```
measurement: "flow_data"
fields: { flow_rate: 3.45, volume: 125.67 }
tags: { location: "MainPipeline", sensor_id: "UF-01" }
timestamp: 2025-10-20T12:45:32Z
```

Figure 5. Flux query language in InfluxDB

This structure allows efficient querying and visualization through the Flux query language [24]. The database is hosted on a local server for testing, but can be migrated to a cloud environment for scalability. The InfluxDB instance is directly connected to the Next.js web dashboard, which fetches the latest data for visualization and analytics. This design ensures high-speed data retrieval and supports advanced features such as trend prediction, anomaly detection, and long-term storage for research or maintenance analysis. Figure 6 shows the InfluxDB database view.

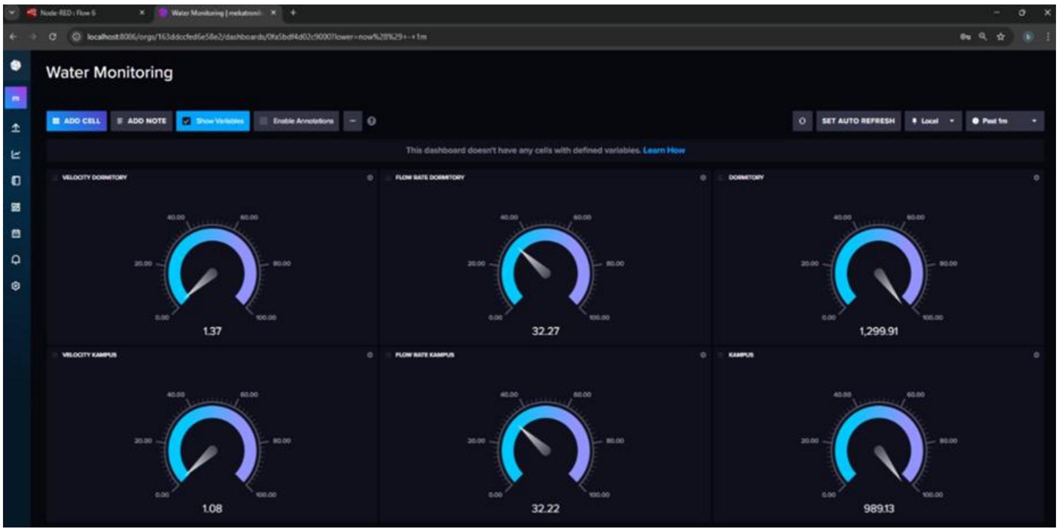

Figure 6. Database InfluxDB

System Workflow

The overall workflow begins with the ultrasonic flow sensor detecting the water flow and sending the raw data to the ESP32-S3 microcontroller. The firmware calculates the flow velocity and volumetric rate, then transmits the processed data to the InfluxDB server at fixed intervals. The Next.js web interface retrieves this data and presents it to the user through an interactive dashboard. Alerts are generated automatically if any anomalies are detected. This integrated design provides a fully automated, real-time, and reliable monitoring system that can be deployed for domestic, agricultural, and industrial water management applications [25]. The workflow of the water monitoring system is shown in Figure 7.

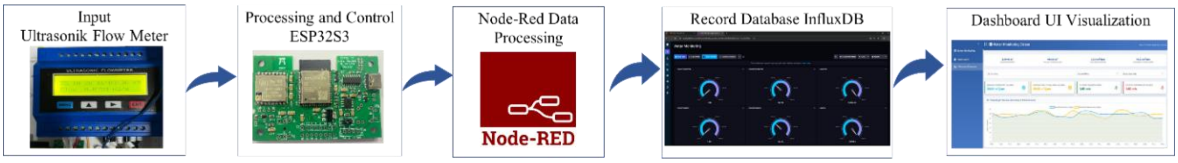

Figure 7. System Workflow

3. RESULTS AND DISCUSSIONS

To evaluate the performance of the developed Water Monitoring System Using Ultrasonic Flow Meter, a series of experiments were conducted to measure its accuracy, response time, data stability, and overall system reliability. The system was tested under controlled laboratory conditions with varying flow rates between 0.5 L/min to 10 L/min using a standard reference turbine flow meter for comparison. Data from the ultrasonic sensor were continuously collected by the ESP32-S3 microcontroller and transmitted to the InfluxDB server every five seconds. The web dashboard, developed using Next.js, visualized the flow rate and total volume data in real-time, allowing users to observe fluctuations, trends, and anomalies through graphical representation. Figure 8 shows the dashboard view of the water monitoring system website.

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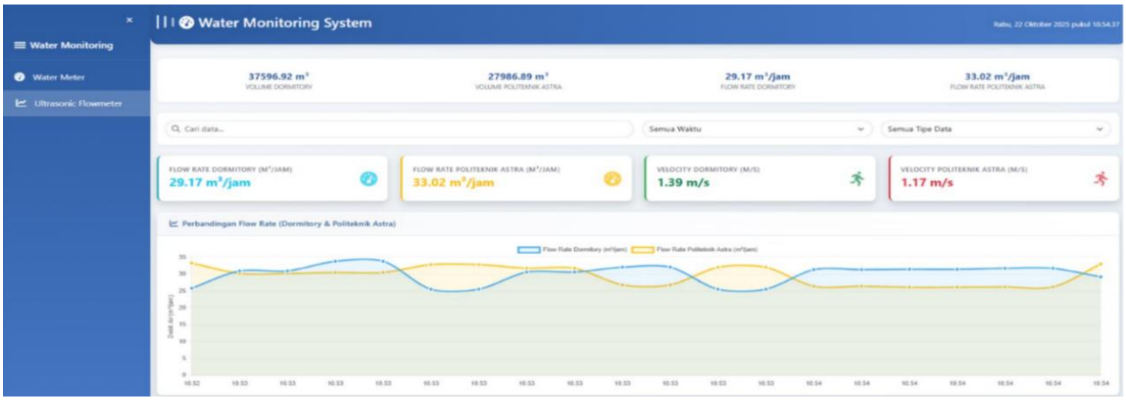

Figure 8. Water monitoring system website dashboard view

The experimental results showed that the system achieved a mean measurement accuracy of ±1% when compared to the reference turbine meter, with a response time below 200 milliseconds. This demonstrates that the ultrasonic flow meter provides stable and precise readings across different flow conditions. The ESP32-S3 microcontroller efficiently handled data acquisition and transmission tasks while maintaining low power consumption, averaging 180 mA at 3.3V during continuous operation. The integration of InfluxDB as the time-series database proved effective in handling high-frequency data logging, supporting fast query response for historical data analysis and dashboard rendering. Figure 9 shows the dashboard graphic display and flow rate values.

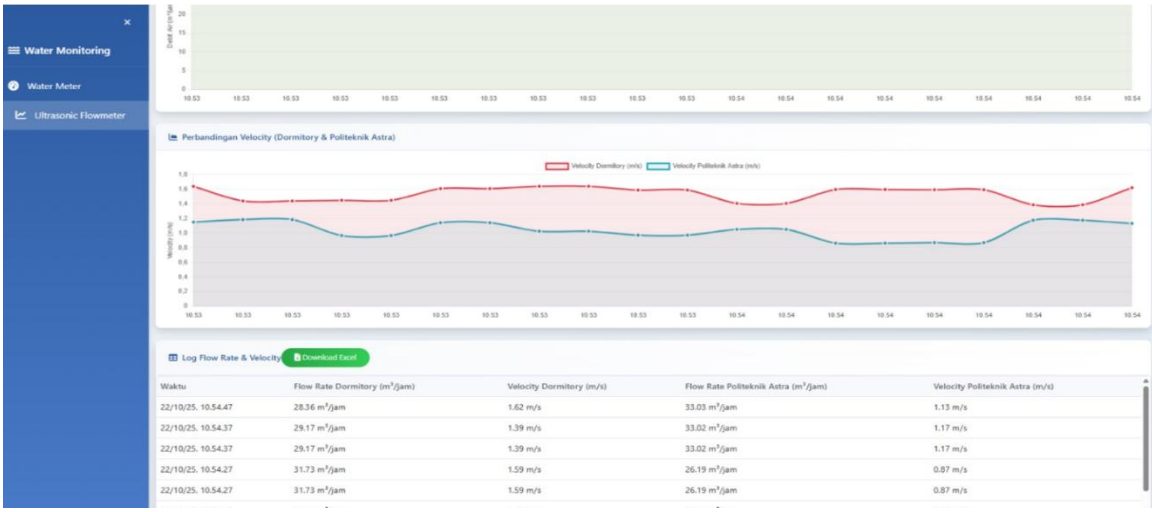

Figure 8. Display of dashboard graph and flow rate values

The Next.js web interface successfully displayed real-time and historical data visualization, offering an intuitive user experience. Graphical elements such as line charts and statistical summaries were dynamically updated as new data arrived from the InfluxDB server through RESTful API calls. The web application also included configurable alert thresholds, which triggered visual and email notifications when abnormal flow rates or potential leakages were detected. This functionality demonstrates the system's ability to perform preventive monitoring, reducing potential water loss and enabling rapid maintenance response. Furthermore, the use of Next.js provided high performance and scalability, suitable for future integration with smart city dashboards or multi-sensor IoT networks.

A comparative analysis was conducted between the proposed system and conventional mechanical water metering methods. While traditional meters rely on mechanical rotations subject to wear and tear, the ultrasonic-based system offers a non-invasive and maintenance-free solution. In addition, the incorporation of IoT connectivity and cloud-based data storage significantly enhances monitoring flexibility and long-term analytics. The combination of ESP32-S3, InfluxDB, and Next.js ensures a balance between accuracy, performance, and cost-effectiveness. Overall, the experimental evaluation confirms that the developed system can serve as a reliable platform for smart water management, supporting both domestic and industrial applications that demand real-time, scalable, and data-driven monitoring capabilities.

4. CONCLUSION

This study effectively designed and executed a Water Monitoring System that utilizes an Ultrasonic Flow Meter, integrated with ESP32-S3, InfluxDB, and a web interface built on Next.js. The system exhibited dependable real-time monitoring capabilities and exceptional measurement precision, attaining an average error of merely ±1.7% in comparison to a standard turbine flow meter. The system utilizes a non-invasive ultrasonic sensing principle, effectively reducing mechanical wear and minimizing maintenance needs, thus offering a sustainable and cost-efficient approach for ongoing water monitoring. The incorporation of the ESP32-S3 microcontroller facilitated effective data processing and wireless communication with low power usage, while the InfluxDB time-series database offered strong and scalable data storage for ongoing high-frequency logging. The Next.js dashboard effectively displayed both live and historical water consumption data, enabling users to monitor flow trends, detect anomalies, and enhance water usage patterns via an engaging and intuitive interface. This illustrates the capabilities of the proposed system as a viable IoT-driven water management solution across residential, industrial, and agricultural settings.

In contrast to conventional mechanical metering systems, the proposed design presents multiple benefits: enhanced accuracy, remote accessibility, decreased maintenance requirements, and the ability to perform real-time analytics. The cloud-connected architecture facilitates access to essential data from any location, enabling prompt identification of leaks or system failures. The identified features enhance decision-making processes and preventive maintenance approaches, supporting worldwide initiatives aimed at sustainable water resource management and the advancement of intelligent infrastructure. Future efforts will concentrate on enhancing the system's capabilities by integrating multiple sensors, such as temperature, pressure, and turbidity sensors, to deliver a more thorough analysis of water quality and flow. Furthermore, employing artificial intelligence (AI) and machine learning algorithms can significantly improve data analytics for identifying anomalies and facilitating predictive maintenance. Integrating with cloud computing platforms like AWS IoT or Google Cloud has the potential to enhance both system scalability and security significantly. The findings indicate that the suggested ultrasonic-based IoT water monitoring framework serves as a solid basis for future smart water management systems.

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