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Experimental Evaluation of an Automated Precipitation Sampling Prototype for Isotopic Monitoring in Remote Scenarios.

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Abstract– Reliable precipitation sampling is essential for stable isotope analysis in hydrology and climate studies, particularly in remote regions where frequent access to monitoring stations is limited. Under such conditions, accumulated sampling over several days is commonly adopted, increasing the risk of cross-contamination and reducing the temporal resolution of isotopic data. This work presents the design and experimental evaluation of an automated precipitation sampling prototype intended to explore the feasibility and limitations of reducing cross-contamination through sequential sample separation. The system integrates commercially available water-level sensors, electromechanical actuators, and a microcontroller-based control architecture, and is evaluated under controlled laboratory conditions. Experimental results show that the conductive water-level sensor provides stable and repeatable measurements once a measurable water level is established, with no significant dependence on water pH or conductivity within the tested range. However, a significant dead volume driven by container geometry and sensor placement introduces systematic detection delays at low flow rates. At the system level, partial automation is achieved, but fully autonomous operation is limited by actuator performance and fixed-threshold control logic. The main contribution of this work lies in the experimental identification of practical limitations and failure modes associated with affordable automated precipitation sampling systems, providing guidance for future designs aimed at improving reliability, autonomy, and suitability for isotopic precipitation monitoring in resource-constrained environments.

Keywords-- Precipitation sampling; Stable isotope hydrology; Water-level sensors; Sensor characterization; Environmental monitoring

I. Introduction

The analysis of stable isotopes in precipitation has become a fundamental tool in hydrology, meteorology, and climate science, particularly for understanding water sources, atmospheric processes, and groundwater recharge mechanisms [1],[2].

However, the reliability of isotopic data depends not only on laboratory techniques, but also on the quality and integrity of the collected samples. In many monitoring networks—especially those operating in developing regions or remote environments—the process of precipitation sampling remains logistically challenging and prone to systematic errors.

One of the most critical challenges in isotopic precipitation monitoring is the risk of cross-contamination between samples collected over multiple days. In stations where daily access is not feasible, rainfall is often accumulated in a single container for extended periods, typically one week or even one month. This practice prevents the temporal separation of individual precipitation events and compromises the isotopic resolution of the resulting dataset. Additionally, prolonged exposure of collected samples to environmental conditions such as solar radiation and temperature fluctuations may alter their original physicochemical properties, further degrading data quality.

In Honduras, the local network of isotopic monitoring stations operates under varying sampling regimes, including daily, weekly, and monthly accumulation [3],[4]. While daily sampling provides higher temporal resolution, it requires consistent human intervention and site accessibility, which are not always feasible in remote or resource-limited locations. These operational constraints highlight the need for automated or semi-automated sampling approaches capable of preserving sample integrity while reducing the frequency of site visits.

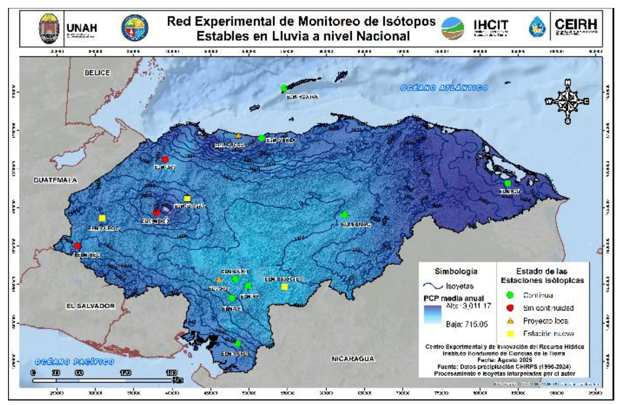

Fig. 1 Geographic distribution of monitoring stations within the local precipitation isotope network in Honduras (map provided by J. O. Hernández-Ortiz, IHCIT)

Several commercial precipitation collectors are currently available, primarily designed for long-term unattended operation and sample preservation [5]. However, these systems are generally optimized for cumulative collection rather than for systematic daily or event-based sample separation. As a result, their suitability for applications requiring high temporal resolution in isotopic analysis is limited, particularly in small-scale or academic monitoring programs where cost, operational complexity, and maintenance requirements also represent practical constraints.

This work presents the design, construction, and experimental evaluation of an automated precipitation sampling prototype intended to reduce cross-contamination between samples and enable improved temporal separation under remote monitoring scenarios. The system integrates water-level sensors, electromechanical valves, and a microcontroller-based control architecture to sequentially manage the collection of precipitation volumes. Rather than focusing solely on functional demonstration, this study emphasizes the quantitative characterization of sensor behavior, system response, and volumetric limitations under controlled laboratory conditions.

Unlike many studies that primarily focus on the successful functional demonstration of low-cost environmental sensors, the primary novelty of this work lies in its systematic experimental evaluation and explicit reporting of failure modes. By rigorously quantifying sensor variability, geometric limitations, and actuator performance under controlled conditions, this study provides a realistic assessment of the boundaries of affordable automation, filling a critical gap in the literature regarding the actual deployment viability of such systems.

The results provide insight into the practical challenges associated with automated sampling under constrained design conditions, including sensor variability, dead volume effects, and limitations in achieving fully autonomous operation using standard hydraulic components. These findings contribute to the ongoing discussion on the feasibility and reliability of affordable instrumentation for environmental monitoring and offer guidance for future designs aimed at improving temporal resolution and robustness in isotopic precipitation sampling deployed in remote regions.

II. Background and Related Work

Stable isotope analysis of precipitation has been widely used to investigate hydrological processes, atmospheric circulation patterns, and climate variability. Typical ranges of stable isotope compositions associated with major components of the hydrological cycle are illustrated in Fig. 2. International initiatives such as the Global Network of Isotopes in Precipitation (GNIP), coordinated by the International Atomic Energy Agency (IAEA) and the World Meteorological Organization (WMO), have established standardized protocols for sample collection and long-term monitoring. These protocols emphasize the importance of minimizing evaporation, contamination, and mixing between samples to preserve the original isotopic signature of rainfall events.

Despite the availability of standardized guidelines, practical implementation remains challenging, particularly in regions with limited infrastructure or difficult access. In many monitoring stations, precipitation samples are collected manually, requiring frequent site visits and trained personnel. When daily sampling is not feasible, accumulated sampling strategies are often adopted, which inherently reduce temporal resolution and increase the risk of cross-contamination between precipitation events. These limitations are especially critical for studies seeking to capture short-term isotopic variability or event-based dynamics.

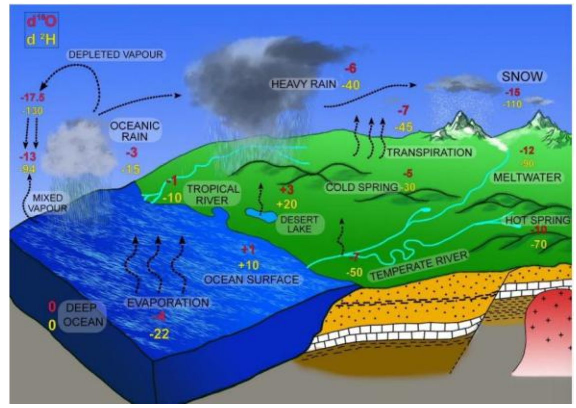

Fig. 2 Estimated typical stable isotope compositions associated with major components of the hydrological cycle [1].

To address these challenges, a range of automated precipitation collectors has been developed, spanning from purely mechanical devices to electronically controlled systems. In the commercial sector, specialized systems such as the Eigenbrodt NSA 181 represent state-of-the-art hardware, providing high-precision sequential sampling with integrated cooling and automated sealing to prevent evaporative fractionation. However, the high capital investment and specialized maintenance required for such proprietary platforms often render them inaccessible for emerging monitoring networks or academic pilot studies in developing regions. Conversely, while academic open-source alternatives have successfully lowered the barrier to entry using microcontroller-based architecture, they frequently focus on functional validation while underreporting the physical constraints of the hardware. Specifically, many low-cost designs overlook the systematic characterization of hydraulic dead volume and the operational inconsistencies introduced by standard PVC fittings and generic solenoid valves, critical factors that this work seeks to quantify and model.

Water-level sensing technologies frequently employed in these systems include conductive and capacitive sensors [6]. Conductive sensors offer implementation simplicity but depend on the electrical properties of the fluid, which can vary significantly in natural precipitation. Capacitive sensors provide non-contact measurements but are sensitive to container geometry and environmental interference. The behavior of both sensor types under conditions representative of low-conductivity rainwater and confined sampling geometries remains insufficiently characterized in the literature.

Furthermore, the integration of sensing elements with electromechanical components such as solenoid valves and small pumps introduces additional sources of uncertainty. Dead volume effects, response delays, incomplete sealing, and inconsistent actuation can significantly affect volumetric accuracy and limit achievable levels of automation. These practical constraints are often underreported, despite their relevance for real-world sampling scenarios.

Within this context, the present work contributes an experimental evaluation of an automated precipitation sampling prototype aimed at improving temporal separation and reducing cross-contamination between samples. Emphasis is placed on the quantitative characterization of sensor behavior, volumetric response, and system-level limitations under controlled laboratory conditions, rather than on the demonstration of a finalized field-ready device.

III. SYSTEM DESCRIPTION

This section describes the architecture, components, and operating logic of the automated precipitation sampling prototype evaluated in this study. The system was conceived as a modular solution intended to explore the feasibility and limitations of automated sample separation using commercially available components compatible with the initial design constraints.

Fig. 3 Physical assembly of the automated precipitation sampling prototype, detailing the collection chamber, hydraulic lines, and distribution valves.

A. System Architecture

The prototype follows a centralized control architecture based on a microcontroller platform responsible for sensor acquisition, decision-making, and actuator control. The system is designed to manage the collection and routing of precipitation volumes into separate containers in a sequential manner [7], with the objective of reducing cross-contamination between samples collected over different accumulation periods.

The overall system is composed of three main subsystems:

1) *Sensing.*
2) Control and data acquisition.
3) Hydraulic actuation and distribution.

This modular structure allows individual subsystems to be evaluated independently while maintaining integrated system operation during experimental testing.

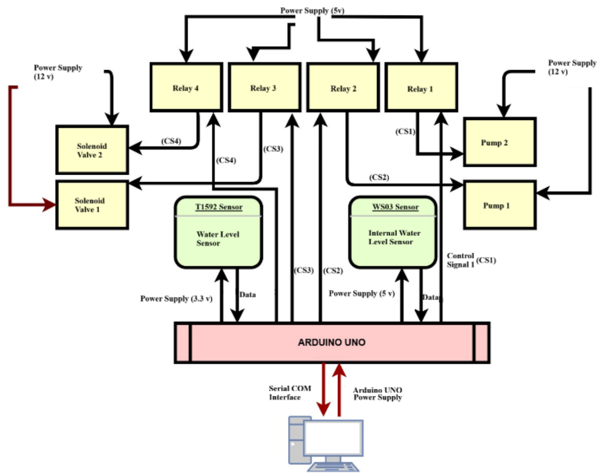

Fig. 4 High level schematic diagram of the system architecture.

B. Sensing Subsystem

Two water-level sensing technologies are incorporated into the system to monitor different stages of the sampling process. The primary sensing element is a conductive water-level sensor T1592 [8] installed along the main collection path. This sensor provides a continuous analog signal proportional to the immersion depth of its conductive tracks. The signal is acquired using the microcontroller's internal 10-bit analog-to-digital converter (ADC), enabling real-time monitoring of water accumulation.

To mitigate corrosion and electrochemical degradation, the conductive sensor is powered only during measurement intervals. Its supply voltage is controlled by a digital output of the microcontroller, which activates the sensor briefly prior to each reading and disables it immediately afterward.

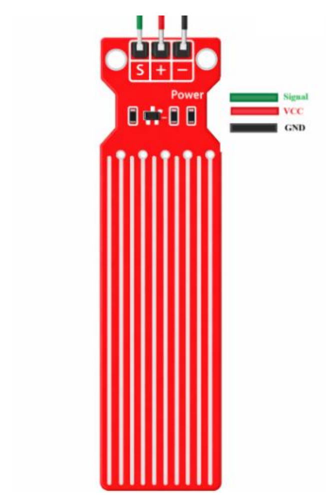

Fig. 5 Visual representation of the conductive water level sensor T1592

A capacitive water-level sensor is installed externally on the distribution container. Unlike the conductive sensor, it operates without direct contact with the water and functions as a threshold detector, indicating when a predefined accumulation level has been reached. This sensor is used primarily to support control decisions related to sample transfer between containers.

C. Control Unit and Interface

System control is implemented using an Arduino-based microcontroller platform operating at 5 V [9],[10]. The control unit is responsible for acquiring analog signals from the sensing subsystem, evaluating predefined logical conditions, actuating hydraulic components through relay modules, and transmitting diagnostic and measurement data via a serial communication interface.

During experimental operation, sensor readings, actuator states, and timing information are transmitted in real time to an external computer through the serial port and logged for subsequent analysis and validation. The control strategy is rule-based and relies on threshold evaluation, without incorporating adaptive algorithms or closed-loop feedback control.

D. Hydraulic Actuation and Distribution Subsystem

Water routing and sample handling are achieved using a combination of solenoid valves and low-voltage DC water pumps [11]. The solenoid valves operate in a normally closed configuration and are used to direct water flow toward designated sample containers. Pumps are employed to assist fluid transfer and to reduce stagnation within the hydraulic network.

Fig. 6 Normally-closed 12V DC solenoid valve employed for sequential sample routing.

Due to the electrical requirements of these actuators, relay modules are used to provide electrical isolation between the low-voltage control circuitry and the power stage. The hydraulic components are powered by an external 12 V DC supply, while the microcontroller and sensors operate independently at low voltage. The hydraulic layout is constructed using PVC fittings and flexible tubing. While this configuration facilitates rapid prototyping and system reconfiguration, it introduces geometric constraints that influence fluid dynamics, sensor response, and volumetric accuracy. These effects are examined experimentally in later sections.

E. Operating Logic

The system operates according to a predefined sequential control logic. When precipitation is detected and water begins to accumulate, the conductive sensor monitors the rising water level along the collection path. Once a predefined threshold is reached, the control unit activates the corresponding valve filling the separation container and subsequently activating the pump to transfer the collected volume into a designated sample container. After sample transfer, the system resets and awaits the next accumulation cycle. This sequence is repeated for subsequent samples using the same operational logic. All threshold values and timing parameters are defined prior to operation and remain fixed throughout the experiments.

While this approach enables basic automation of the sampling process, it does not compensate for variations in flow conditions, sensor drift, or mechanical inconsistencies. As a result, the degree of achievable autonomy is limited under the present control strategy.

IV. EXPERIMENTAL METHODOLOGY

The experimental methodology was designed to evaluate the performance and limitations of the proposed automated precipitation sampling system under controlled laboratory conditions [12]. Rather than focusing on field deployment, the experiments aim to characterize sensor behavior, volumetric response, and system operation in a reproducible and traceable manner.

A. Experimental Setup

All experiments were conducted using the complete prototype described in Section III. In addition, selected tests were performed using simplified configurations to isolate the behavior of individual components, with particular emphasis on the conductive water-level sensor. Controlled volumes of water were introduced into the system using graduated syringes and laboratory glassware. Flow rates were regulated manually to simulate precipitation accumulation at predefined rates, primarily 1 mL/min and 2 mL/min. These values were selected to represent low-intensity rainfall conditions and to enable detailed observation of sensor response over time.

Volumetric measurements were referenced against a calibrated graduated cylinder compliant with DIN 58667 standards. The cylinder features a collection area of 200 cm^2 and a minimum graduation of 1 mm, making it suitable for precipitation-related validation tasks.

B. Sensor Characterization Procedure

The conductive water-level sensor was characterized by progressively increasing the water volume within the collection container while continuously acquiring its analog output. Sensor readings were digitized using the microcontroller's 10-bit analog-to-digital converter (ADC).

To evaluate the influence of water composition, experiments were performed using multiple water samples with different physicochemical properties, including tap water and distilled water. Parameters such as pH, conductivity, and temperature were measured before and after each experimental run using portable laboratory instruments.

For repeatability analysis, selected experiments were repeated using two nominally identical conductive sensors under identical conditions. This allowed assessment of sensor-to-sensor variability and the impact of sensor cleanliness on measurement stability.

The capacitive sensor was evaluated qualitatively as a threshold detector by verifying its ability to consistently identify the attainment of a predefined water level within the distribution container.

C. Data Acquisition and Processing

During experimental operation, the microcontroller transmitted time-stamped sensor readings, actuator states, and control events through a serial interface. These data were captured using a custom Python-based data acquisition script and stored in comma-separated value (CSV) format for post-processing. Data analysis was performed using standard scientific computing tools. Time-series plots were generated to visualize filling curves, sensor response dynamics, and activation events. In order to facilitate comparison between experiments conducted under different conditions, selected datasets were normalized in time and amplitude.

D. Validation Strategy

System validation focused on two primary aspects: volumetric accuracy and sample separation performance. Volumetric accuracy was evaluated by comparing sensor-derived measurements with reference volumes obtained from the graduated cylinder. Particular attention was given to identifying and quantifying dead volume, defined as the volume of water introduced into the system before the sensor begins to register a measurable response.

Sample separation performance was assessed operationally by executing predefined sampling sequences and inspecting the resulting containers to confirm that each sample remained isolated. While this evaluation was qualitative, it provided direct evidence of the system's ability, or limitations, in preventing cross-contamination under the tested conditions.

E. Experimental Limitations

All experiments were performed under controlled laboratory conditions. Environmental factors such as wind, temperature fluctuations, solar radiation, and long-term exposure effects were not considered in this phase of the study. In addition, actuator performance was evaluated only in terms of functional integration rather than long-term durability or field reliability.

These limitations were intentionally accepted in order to focus the study on sensor behavior and system-level feasibility, and they provide a clear basis for future work oriented toward field validation.

V. Results

This section presents the experimental results obtained during the laboratory evaluation of the automated precipitation sampling prototype. The results are organized according to sensor characterization, volumetric response, and system-level performance, with emphasis on reproducibility and observed limitations.

A. Conducting Sensor Response and Filing Curves

The conductive water-level sensor exhibited a consistent monotonic increase in output signal as water volume increased within the container. For all tested flow rates, the sensor response followed a nonlinear filling curve, with higher sensitivity observed at intermediate immersion depths. When experiments were repeated using water samples with different physicochemical properties, including tap water and distilled water, no significant differences were observed in the overall shape of the response curves within the tested range. The sensor produced stable readings under both low- and moderate-conductivity conditions, provided that the sensing tracks were clean prior to each run.

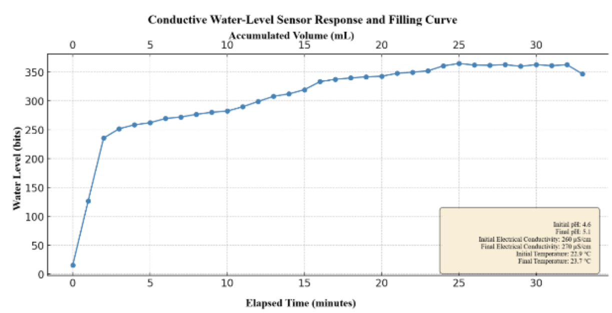

Fig. 7 Smoothed water-level response of the conductive sensor for Sample 3, showing the nonlinear filling behavior as a function of accumulated water volume (1 mL per minute).

To evaluate repeatability, two nominally identical conductive sensors were tested under identical conditions. Although both sensors exhibited similar qualitative behavior, noticeable differences were observed in their maximum digital output values and slope characteristics.

As explicitly shown in Fig. 8, while both sensors follow a similar non-linear trend, Sensor 2 saturates at a higher digital value and exhibits a steeper initial slope. These visual discrepancies indicate a lack of intrinsic standardization between sensors of the same model.

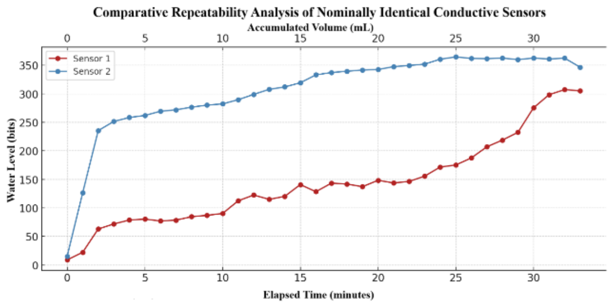

Fig. 8 Comparative response of two nominally identical conductive water-level sensors T1592 under identical operating conditions.

B. *Effects of Sampling Rate*

Sensor response was evaluated at different sampling rates, ranging from high-frequency acquisition to downsampled datasets representing one to two samples per minute. While high-frequency acquisition captured short-term fluctuations and noise, downsampled datasets provided smoother filling curves and clearer visualization of the accumulation process.

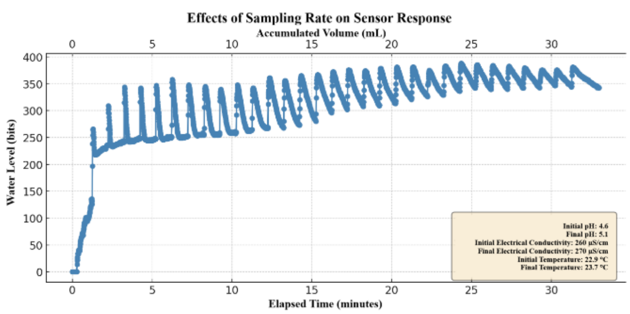

Fig. 9 High-frequency water-level measurements obtained from Sensor 2, illustrating short-term fluctuations.

No loss of relevant volumetric information was observed when using lower sampling rates for the tested flow conditions. This suggests that reduced sampling frequencies may be sufficient for precipitation monitoring applications, provided that system dynamics remain slow relative to the sampling interval.

C. *Volumetric Accuracy and Dead Volume*

A consistent dead volume was observed across all experiments, defined as the volume of water introduced into the system before the sensor registered a measurable response. This effect was particularly evident during Experiment 2 where tests were conducted with the final prototype, in which the collection container volume was increased. At a flow rate of 2 mL/min, the sensor began registering true nonzero output values only after approximately 18 minutes, corresponding to an accumulated volume of approximately 36 mL. As illustrated by the flat baseline from t=0 to t=18 in Fig. 10, the system receives fluid without generating any sensor response during this initial phase. This dead volume was attributed to the geometric configuration of the collection container and the vertical placement of the sensor. Once the dead volume threshold was exceeded, the sensor response became continuous and repeatable.

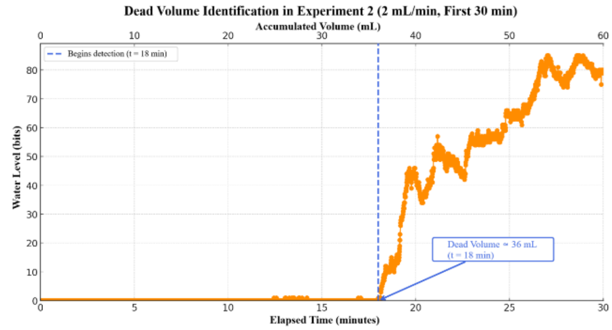

Fig. 10 Dead volume identification at a flow rate of 2 mL/min, showing delayed sensor response until an accumulated volume is reached.

When comparing experiments conducted in a graduated cylinder and in the full prototype, normalized filling curves exhibited similar shapes. However, the maximum digital output values differed significantly between configurations, with the prototype exhibiting a reduction of approximately 30% in peak sensor readings. This result highlights the influence of container geometry on sensor calibration.

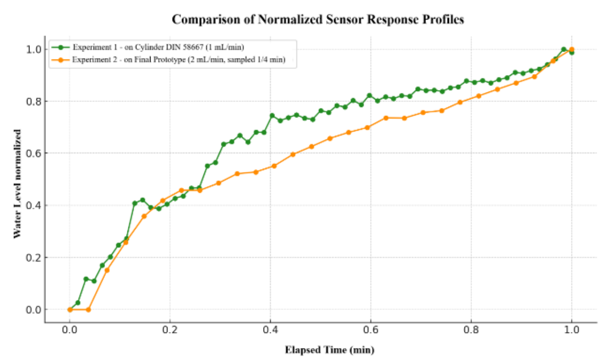

Fig. 11 Comparison of normalized time and water-level response profiles for two experimental containers.

D. *Mathematical Modeling of Sensor Response*

Following the identification of the dead volume threshold, a polynomial regression was applied to the experimental data to model the relationship between introduced volume and sensor output. A third-order polynomial provided the best fit for the post-threshold data. As depicted in Fig. 12, this third-order fit models the steeper initial sensitivity of the sensor and its gradual saturation at higher volumes.

$$y = 0.0003588x^3 - 0.0126x^2 + 1.99x + 35.89 \,. \qquad (1)$$

Where:

y= represents the water level

x= represents the volume poured into the system in ml

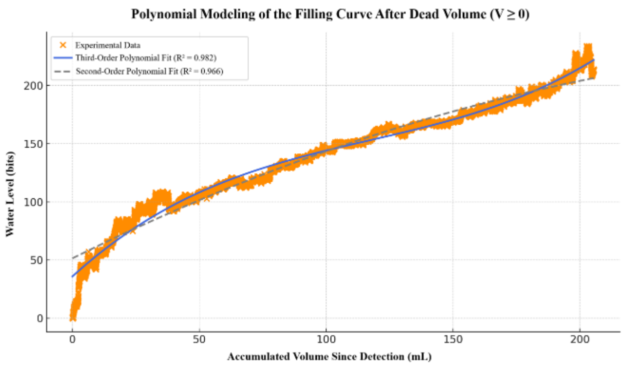

Fig. 12 Polynomial modeling of the filling curve for Experiment 2 after dead volume compensation.

The resulting model demonstrated good agreement with experimental measurements under consistent conditions. However, variations in sensor characteristics and container geometry limited the direct transferability of a single calibration model across different system configurations.

E. *Sample Separation Performance*

Sample separation tests were conducted by executing predefined sampling sequences and monitoring the distribution of collected water among individual containers. While the system was able to route water sequentially under operator supervision, fully autonomous operation was not consistently achieved.

Manual intervention was required in several trials due to incomplete valve closure, delayed actuation, or insufficient pumping force. These issues prevented reliable isolation of samples without human oversight under the tested conditions.

F. *Summary of Observed Performance*

Overall, the results demonstrate that the proposed system is capable of detecting water accumulation and characterizing volumetric behavior under controlled laboratory conditions. The conductive sensor provided stable and repeatable measurements once the dead volume was exceeded, and the system-level data acquisition functioned reliably.

However, limitations related to sensor variability, geometric effects, and actuator performance constrained the system's ability to achieve fully autonomous sample separation.

VI. Discussion

A. *Sensor Behavior and Reliability*

The experimental results demonstrate that the conductive water-level sensor exhibits a stable and repeatable response once a measurable water level is established. Within the range of pH and conductivity values evaluated, no significant dependence of sensor output on water composition was observed. This result was unexpected, given the operating principle of conductive sensors, and suggests that under controlled laboratory conditions the sensor response is dominated by geometric immersion rather than by ionic concentration.

However, notable variability was observed between nominally identical sensors. Differences in maximum digital output values and response slopes indicate a lack of intrinsic standardization, which limits the transferability of calibration parameters between devices. Additionally, sensor cleanliness was found to play a critical role in measurement stability, reinforcing the need for periodic maintenance or alternative sensing strategies in long-term deployments.

B. *Dead Volume and Geometric Effect*

A key finding of this study is the presence of a significant dead volume, defined as the volume of water introduced into the system before the sensor registers a measurable response. This effect is primarily attributed to the geometric configuration of the collection container and the vertical positioning of the sensor relative to the inlet.

The existence of dead volume introduces a systematic delay in detection and directly affects volumetric accuracy, particularly at low flow rates. While this effect can be compensated through calibration, it reduces the effective sensitivity of the system and complicates direct interpretation of accumulated volume. The observed differences in maximum sensor output between the graduated cylinder and the full prototype further highlight the strong influence of container geometry on sensor behavior.

These results underscore the importance of considering geometric constraints early in the design of automated sampling systems, especially when low-cost sensors are used in confined or non-ideal configurations.

To mitigate the identified dead volume in future iterations, a couple design modifications are proposed. Transitioning from standard cylindrical PVC caps to conical-bottom collection chambers would facilitate the immediate channelling of the initial droplets toward the sensor tracks. Reducing the internal diameter of the hydraulic lines and minimizing the distance between the intake and the first valve would decrease the volume required to prime the system, potentially improving sensitivity to low-intensity precipitation events.

C. *System-Level Limitations and Autonomy*

Although the system successfully demonstrated automated detection and partial routing of collected water, fully autonomous operation was not consistently achieved. Limitations were primarily associated with actuator performance, including incomplete valve closure, delayed response times, and insufficient pumping force under certain conditions.

The control logic employed in this study relies on fixed thresholds and predefined timing parameters. While this approach enables basic automation, it lacks the adaptability required to compensate for mechanical variability, flow inconsistencies, and component aging. As a result, human intervention was necessary in several trials to ensure correct sample separation.

The transition from a fixed-threshold, open-loop control logic to a closed-loop control logic is essential for achieving true autonomy. Integrating a low-flow liquid flow meter or utilizing the secondary capacitive sensor for continuous volumetric feedback would allow the system to dynamically adjust pump duty cycles and valve timing. Additionally, incorporating automated self-calibration routines, where the microcontroller references the sensor's baseline resistance in a dry state could compensate for the electrode fouling and sensor drift observed during laboratory trials, ensuring long-term measurement stability.

These findings illustrate a critical distinction between automated and autonomous systems. While automation can be achieved using simple control strategies and low-cost components, reliable autonomy requires tighter integration between sensing, actuation, and control, as well as more robust hardware selection.

D. *Implications for Low-Cost Environmental Instrumentation*

The results of this study reflect broader challenges associated with low-cost instrumentation for environmental monitoring. While accessible components and open-hardware platforms enable rapid prototyping and experimentation, their performance under realistic operating constraints is often overestimated.

This work highlights the importance of rigorous experimental validation, particularly for applications where data integrity is critical. Reporting system limitations and failure modes is essential to avoid unrealistic expectations and to guide future development efforts. In this context, the value of the present study lies not in presenting a finalized field-ready solution, but in providing quantitative insight into the trade-offs inherent to affordable automation strategies.

E. *Design Guidelines for Future Iterations*

Based on the experimental findings, several practical guidelines can be identified for future designs of automated precipitation sampling systems:

1) Sensor placement and container geometry should be optimized to minimize dead volume.
2) Calibration procedures must account for sensor-to-sensor variability and system geometry.
3) Conductive sensors require maintenance considerations to ensure long-term stability.
4) Actuator selection should prioritize reliability and repeatability over nominal specifications.
5) Control strategies should incorporate feedback mechanisms or adaptive logic when autonomy is required.

The roadmap toward a field-ready version of the system necessitates addressing several environmental challenges. Physical protection via UV-stabilized conduits and NEMA-rated enclosures is required to withstand long-term exposure to solar radiation and humidity. To prevent debris entry from wind-blown sediment or organic matter, a dual-stage filtration mesh must be integrated into the intake funnel. Regarding power autonomy, the current 12V DC requirement is well-suited for integration with a 20W solar harvesting system and a 7Ah lead-acid battery. Future field trials will focus on evaluating the influence of temperature fluctuations on the conductivity-based sensing logic, potentially requiring a thermal compensation algorithm within the control software.

VII. Conclusions

This work presents the design and experimental evaluation of a low-cost automated precipitation sampling prototype intended to reduce cross-contamination between samples for isotopic analysis in remote monitoring scenarios. The system integrates commercially available sensors, electromechanical actuators, and microcontroller-based control architecture, and was evaluated under controlled laboratory conditions.

Experimental results show that the conductive water-level sensor provides stable and repeatable measurements once a measurable water level is established. Within the range of pH and conductivity values tested, sensor response was not significantly affected by water composition, suggesting that geometric immersion effects dominate under controlled conditions. However, noticeable variability between nominally identical sensors and sensitivity to sensor cleanliness limits the direct transferability of calibration parameters and highlights the need for maintenance or alternative sensing approaches in long-term applications.

A significant dead volume was identified as a key limitation of the system. This effect, driven by container geometry and sensor placement, introduces a systematic delay in detection and impacts volumetric accuracy at low flow rates. While dead volume can be partially compensated through calibration, it reduces effective sensitivity and complicates data interpretation, particularly for low-intensity precipitation events.

At the system level, the prototype demonstrates partial automation of the sampling process but does not achieve reliable fully autonomous operation. Limitations related to solenoid valve performance, pump capacity, and fixed-threshold control logic require human intervention during several experimental trials. These findings emphasize the distinction between basic automation and true autonomy and underscore the importance of robust actuator selection and adaptive control strategies for field-deployable systems.

Overall, the results indicate that affordable automation strategies can support controlled laboratory studies and feasibility assessments; however, significant design improvements are required before deployment in remote or unattended environments. The primary contribution of this work lies in the experimental identification of practical limitations and failure modes associated with automated precipitation sampling systems based on commercially available components. These findings provide guidance for future designs aimed at improving reliability, autonomy, and suitability for long-term isotopic precipitation monitoring.

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