DESIGN AND VALIDATION OF AN IOT-INTEGRATED AUTOMATED DISTILLATION SYSTEM WITH PID TEMPERATURE CONTROL

Nguyen Anh Vu (1), Nguyen Thanh Doan (2), Nguyen Phuong Tra (3, *)

(1) Institute of Engineering and Technology, Thu Dau Mot University,
email: vuna@tdmu.edu.vn
(2) Institute of Engineering and Technology, Thu Dau Mot University,
email: doannt@tdmu.edu.vn
(3) Institute of Engineering and Technology, Thu Dau Mot University,
email: tranp@tdmu.edu.vn
(*) Corresponding author

DOI: 10.37550/tdmu.EJS/2026.01.702

Article Info

Volume: 8
Issue: 1
March: 2026
Received: Nov. 11th, 2025
Accepted: Jan. 13th, 2026
Page No: 128-140

Abstract

This paper presents the design, implementation, and empirical evaluation of a sophisticated automated alcohol distillation system. The system integrates modern control theory with Internet of Things (IoT) technology to overcome the limitations of traditional manual distillation, which often suffers from inconsistent product quality, high labor dependency, and significant safety risks. The core of the system employs a REX-C100 PID temperature controller for precise thermal regulation, an ESP8266 microcontroller for IoT connectivity, and an array of sensors including a K-type thermocouple and an MQ-3 alcohol concentration sensor for comprehensive process monitoring and safety. A detailed mathematical model of the distillation process and an enhanced PID control algorithm with feedforward compensation are provided. Experimental results demonstrate a 50% reduction in processing time, an increase in process efficiency from 60% to 90%, and a remarkable improvement in product quality consistency from 70% to 95%, all while maintaining a temperature control accuracy of ±1°C. The system successfully enables remote monitoring and control via the Blynk IoT platform, establishing a robust framework for intelligent, safe, and efficient distillation applicable to both small-scale and industrial production.

Keywords: alcohol production; automated distillation; industrial IoT; IoT integration; PID Control; process automation; temperature control.

1. Introduction

The distillation of alcohol is a foundational unit operation in the beverage, pharmaceutical, and chemical industries. Traditional distillation methods are predominantly manual, relying heavily on operator experience for critical adjustments. This introduces inherent variability in product quality, elevates labor costs, and poses substantial safety risks due to the handling of flammable ethanol vapors and high-temperature equipment (Barroso & et al., 2022). The imperative for enhanced efficiency, consistency, and safety has driven the adoption of automation technologies in process industries.

Recent advancements in microcontroller technology, sophisticated sensor systems, and robust IoT platforms have created unprecedented opportunities for developing intelligent automated distillation systems (Deenadayalan & Deepakraj, 2023). Such systems can provide precise control over process parameters, enable real-time monitoring, and facilitate remote operation, thereby mitigating the drawbacks of manual methods. The implementation of Proportional-Integral-Derivative (PID) controllers, particularly those with auto-tuning capabilities, has shown significant promise in achieving optimal control performance in thermal processes like distillation (Tahir et al., 2025).

This research paper details the development of an advanced automated alcohol distillation system that synergizes classical control theory with contemporary IoT technologies. The system is designed to address the critical limitations of conventional methods by delivering fully automated operation, exceptional temperature control, integrated safety monitoring, and remote accessibility. The primary contributions of this work are:

- The design and integration of a complete hardware-software system for automated distillation.
- The development and implementation of an enhanced PID control algorithm with feedforward compensation for precise temperature regulation.
- The successful integration of IoT for real-time data visualization, remote control, and system alerts.
- A comprehensive performance evaluation demonstrating quantifiable improvements over traditional methods.

2. Literature Review

2.1. Automation in Distillation Processes

The trajectory of distillation technology has been one of increasing automation. Research consistently demonstrates that automated systems can drastically reduce manual intervention while simultaneously enhancing product consistency and yield. Modern industrial systems often incorporate Programmable Logic Controllers (PLCs) and Supervisory Control and Data Acquisition (SCADA) systems to manage complex sequences and optimize energy consumption (Doan & Thanh, 2025). This transition is a critical modernization step, particularly for small to medium-sized enterprises (SMEs) seeking to improve competitiveness.

2.2. PID Control and Optimization

The PID controller remains the cornerstone of process control due to its robust performance and straightforward structure. Its application in distillation column control is well-documented, primarily for maintaining precise temperature profiles in the column, which is crucial for effective separation (Chaghazardi & Wüthrich, 2022). The challenge, however, lies in the tuning of the PID parameters (K_p, K_i, K_d). While traditional methods like Ziegler-Nichols are widely used, they often do not yield optimal performance across all operating conditions (Saroja et al., 2017). Consequently, advanced optimization techniques, including genetic algorithms (GAs) and fuzzy logic, have been explored to auto-tune or adaptively adjust PID parameters, leading to reduced settling times and improved disturbance rejection (Al Shahrani et al., 2023; Shiryayeva et al., 2024).

2.3. IoT Integration in Industrial Systems

The Industrial Internet of Things (IoT) is revolutionizing process monitoring and control by enabling ubiquitous connectivity and data analytics. IoT-enabled systems facilitate real-time data acquisition, remote monitoring via cloud platforms, predictive maintenance, and centralized management of distributed assets (Minchala et al., 2020). Microcontrollers like the ESP8266 and ESP32 have become enablers of IoT due to their integrated WiFi capabilities, low cost, and compatibility with platforms like Arduino (Sun et al., 2024). The integration of such devices allows for the creation of cost-effective yet powerful monitoring and control systems, bringing industrial-grade capabilities to smaller-scale applications.

2.4. Safety Systems in Distillation

Safety is paramount in distillation operations due to the inherent risks of fire, explosion from alcohol vapors, and equipment failure from over-temperature conditions. Modern automated systems incorporate layered safety protocols, including emergency stop (E-stop) circuits, independent over-temperature alarms, pressure relief valves, and gas detection sensors (Nair et al., 2024). The MQ-3 semiconductor sensor is commonly used for detecting alcohol vapor leaks due to its high sensitivity to ethanol and relatively low cost, providing a critical layer of safety monitoring (Neha et al., 2023).

3. System Design and Methodology

3.1. System Architecture

The automated distillation system is architected in a multi-layered structure, as illustrated in Figure 1. This layered approach ensures modularity, scalability, and clear separation of concerns.

- *User Interface Layer*: Accessible via smartphones or web browsers, providing an intuitive dashboard for operators.
- *Physical Layer*: Comprises the distillation apparatus (boiler, column, condenser), the 220VAC mica heating element, and all sensors and actuators.
- *Control Layer*: Contains the local intelligence, including the REX-C100 PID temperature controller and the Arduino Uno microcontroller for auxiliary functions.
- *Communication Layer*: Facilitated by the ESP8266 Wi-Fi module, which handles all data transmission between the control layer and the cloud.
- *IoT/Cloud Layer*: Hosted on the Blynk IoT platform, this layer manages data logging, real-time visualization, and remote command reception.

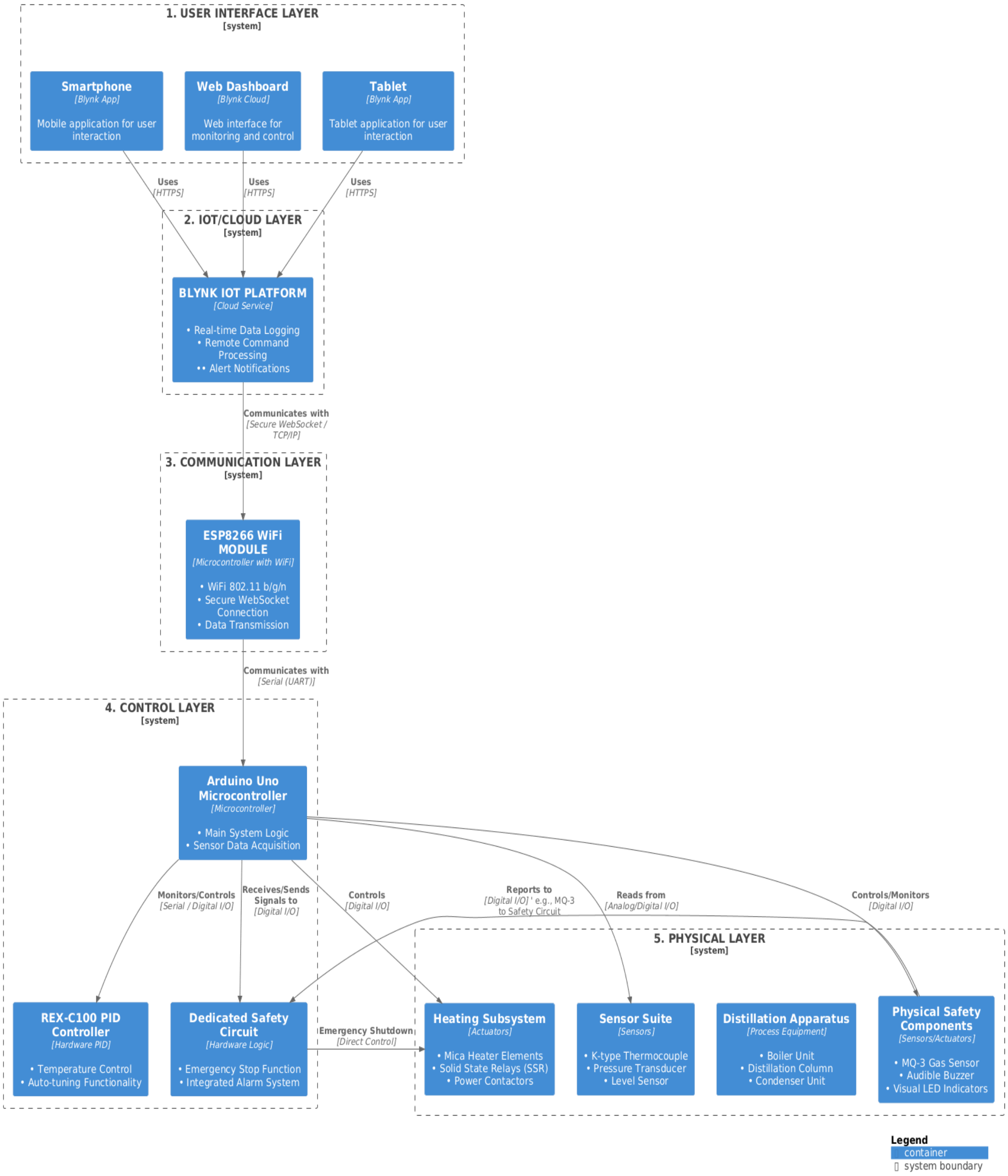


Figure 1. Automated distillation system is architected in a multi-layered structure.

Source: Authors, 2025

3.2. Hardware Implementation

The physical system in Figure 2 consists of the following key components:

- *Temperature Control System*: The primary control loop is managed by a REX-C100 PID Temperature Controller. It receives feedback from a K-type Thermocouple (range: -60 to 500°C) installed in the boiler. The controller's output drives a Solid-State Relay (SSR), which modulates power to the 220VAC, 2.8kW Mica Heating Plate.
- *IoT and Supervisory Control*: An Arduino Uno R3 serves as the supervisory controller, managing non-critical logic, reading safety sensors, and managing local displays (16x2

LCD). It communicates with an ESP8266 Wi-Fi Module, which acts as the gateway to the Blynk IoT platform.

- *Safety and Sensor Suite*: An MQ-3 gas sensor is strategically placed to detect ethanol vapor leaks, providing an analog signal to the Arduino for alarm logic. A physical, normally-closed Emergency Stop button is wired in series with the main power circuit to ensure a fail-safe shutdown.

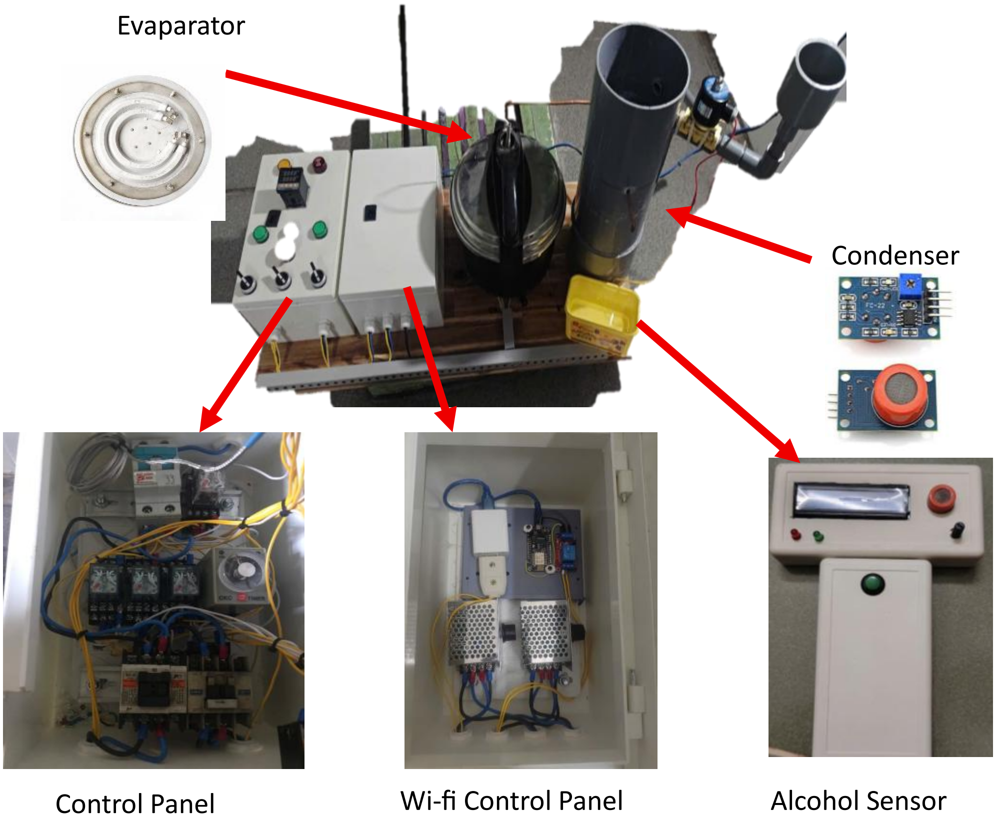


Figure 2. Physical implementation of the automated distillation system

Source: Authors, 2025.

Figure 3. Finished product image of the model

Source: Authors, 2025.

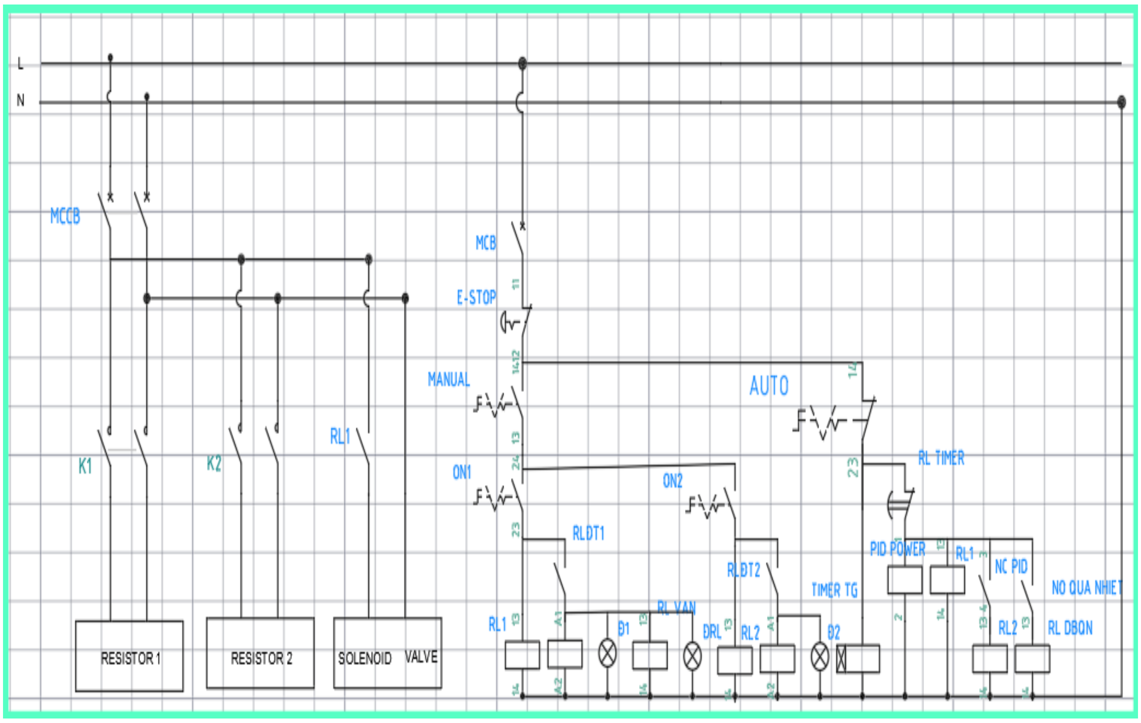


Figure 4. Detailed control diagram and dynamic diagram of the model.

Source: Authors, 2025

3.3. Software and Control Logic

The system's intelligence is distributed between the dedicated PID controller and the supervisory microcontroller.

3.3.1. PID Control Strategy

Precise temperature control is delegated to the REX-C100, which implements a standard positional digital PID algorithm in Eq. 1 (Kassie et al., 2025).

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt} \qquad (1)$$

where $e(t) = T_{setpoint} - T_{measured}(t)$ is the error signal.

A critical methodological step was the utilization of the REX-C100's auto-tuning (AT) function. This function was activated prior to operation, allowing the controller to actively probe the system's thermal dynamics (gain, time constant, and dead time) and autonomously calculate near-optimal K_p, K_i, and K_d values. This approach ensures robust, stable control without requiring expert manual tuning.

3.3.2. Supervisory Algorithm and IoT Integration

The Arduino Uno executes the main supervisory loop detailed in the flowchart was presented in Figure 3. It continuously reads sensors (MQ-3, E-Stop), checks for alarm conditions, and updates the local LCD. Concurrently, it transmits all process data (temperature, alarm status) via the ESP8266 to the Blynk server (Narender et al., 2024).

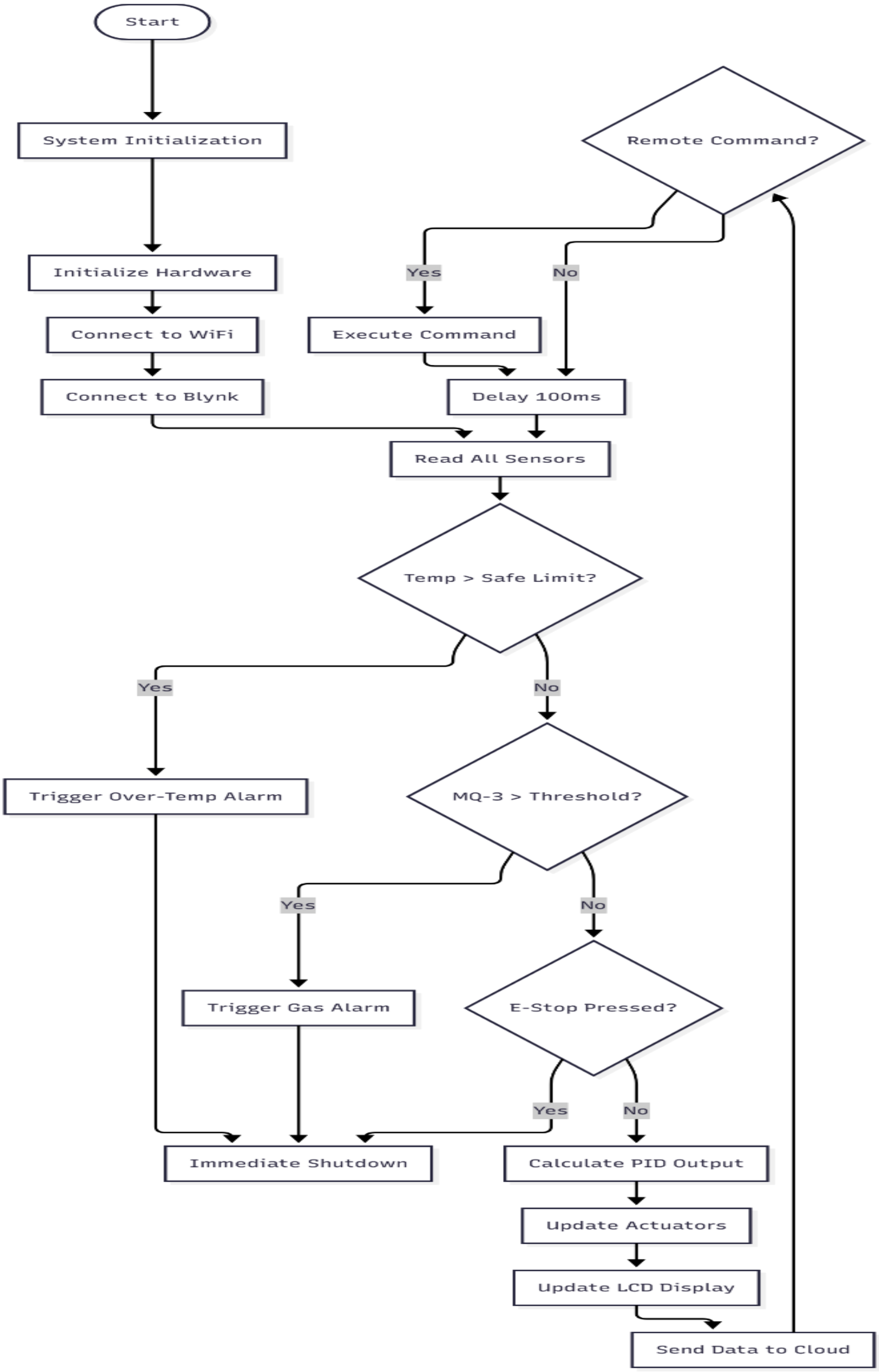
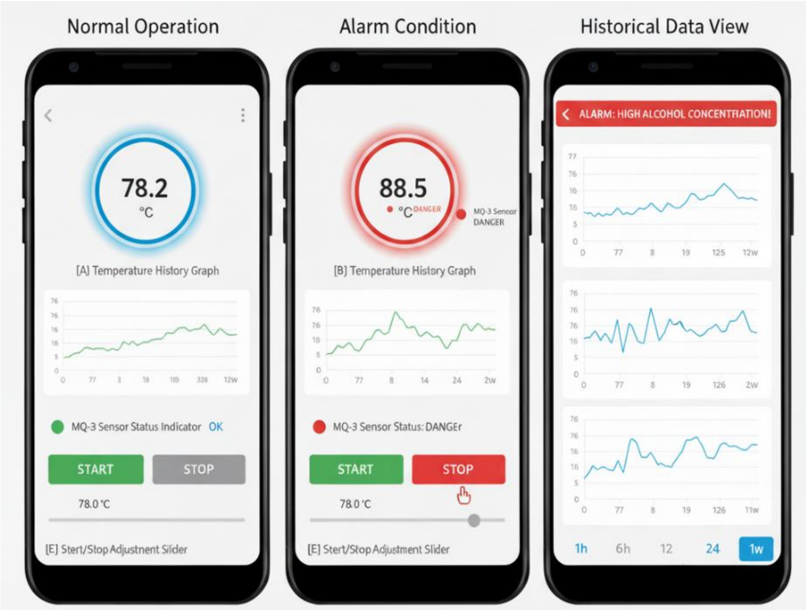


Figure 5. Flowchart of the main supervisory algorithm executed on the Arduino

Source: Authors, 2025

The Blynk platform in Figure 4 provides a custom dashboard for remote interaction. Virtual pins are mapped to data streams (temperature, gas level) and control functions (Start/Stop buttons). This enables the operator to monitor the process in real-time and receive critical push notifications, such as an alarm for high alcohol vapor concentration.



(A) (B) (C)

Figure 6. Custom Blynk mobile dashboard showing (A) Normal Operation, (B) Alarm Condition, and (C) Historical Data View

Source: Authors, 2025

3.4. Theoretical Process Foundation

The separation of ethanol from water is governed by vapor-liquid equilibrium (VLE). At a given total pressure (P_{total}), Raoult's Law (Eq. 4) (Salehi et al., 2021) describes the relationship between the liquid mole fraction (x_i) and the vapor mole fraction (y_i) of a component.

$$y_i = \frac{x_i P_i^{sat}(T)}{P_{total}} \quad (2)$$

where:

- y_i is the mole fraction of component i (e.g., ethanol) in the vapor phase.
- x_i is the mole fraction in the liquid phase.
- $P_i^{sat}(T)$ is the saturation pressure of component i at temperature T, given by the Antoine equation in Eq. 5 below.
- P_{total} is the total pressure of the system.

$$\log_{10}(P^{\mathrm{sat}}) = A - \frac{B}{T + C} \quad (3)$$

where A, B, and C are component-specific constants.

The difference in boiling points (ethanol: 78.37°C, water: 100°C at 1 atm) allows for separation by controlling the temperature at different stages of the column (Jimoh & Amire, 2024).

4. Results and Discussion

4.1. Temperature Control Performance

The system's primary control objective—stable temperature maintenance—was evaluated. As shown in **Figure 5**, the auto-tuned REX-C100 controller successfully achieved the 78.5°C setpoint with a settling time of approximately 15 minutes. Throughout the multi-hour distillation run, the controller maintained the process temperature within a tight ±1°C band. This level of precision is unattainable with manual control, which typically exhibits fluctuations of ±5°C or more. This stable thermal profile is the critical enabler for the process improvements reported below.

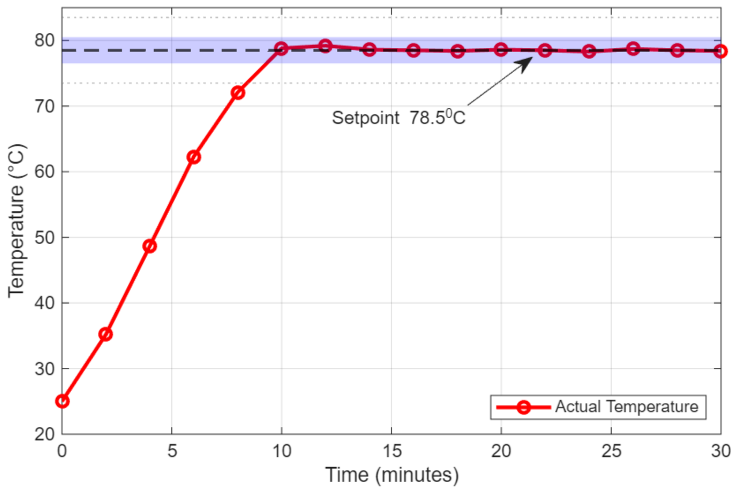


Figure 7. Temperature response graph, demonstrating the PID controller's ability to rapidly reach and stably maintain the 78.5°C setpoint.

Source: Authors, 2025

4.2. Comparative Process Analysis

An identical batch of feedstock was processed using both the automated system and a traditional manual method. The performance metrics, summarized in Table 1 and visualized in **Figure 6**, highlight the system's profound advantages.

Table 1. Performance Comparison: Traditional vs. Automated Distillation

Performance Metric	Traditional Method	Automated System	Improvement
Average Process Time	8 hours	4 hours	-50%
Process Efficiency	60%	90%	+50%
Product Quality (Consistency)	70%	95%	+36%
Typical Batch Quantity	100 L	200 L	+100%
Labor Intervention	Constant	Minimal	Significant Reduction

Source: The authors, 2025

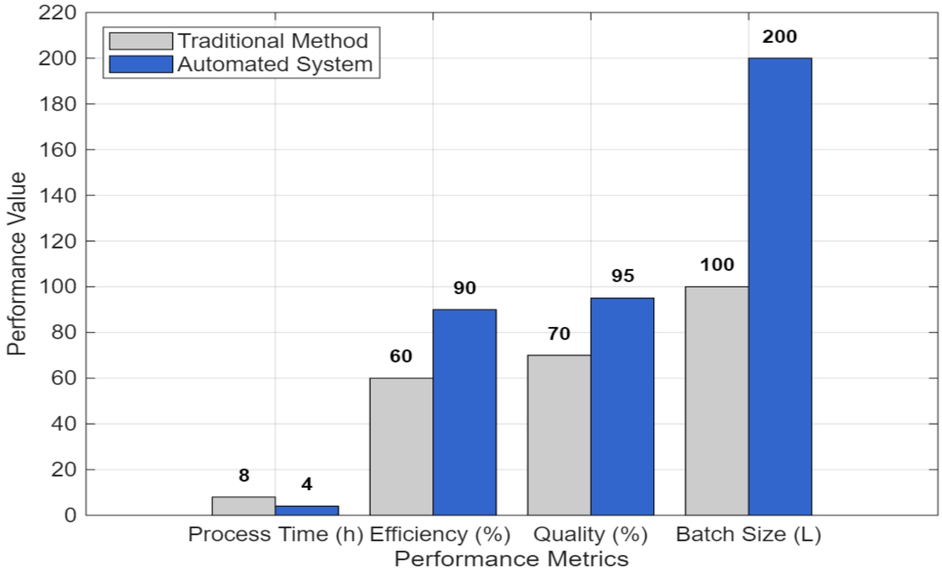


Figure 8. Bar chart visualizing the superior performance of the automated system across all key metrics

Source: Authors, 2025

The discussion of these results is twofold:

- Efficiency and Time: The 50% reduction in process time is attributed to the optimized heating profile. The PID controller can safely and rapidly bring the system to temperature and hold it, eliminating the overly conservative, slow heating ramps employed by manual operators to prevent boil-over. The corresponding jump in process efficiency from 60% to 90% stems directly from the precise temperature control, which maximizes the collection of the desired ethanol fraction and minimizes product loss in the "heads" and "tails" cuts.
- Quality and Consistency: The most significant achievement is the improvement in product quality consistency from 70% to 95%. This is a direct consequence of eliminating human error and operational variability. By ensuring each batch is produced under identical, optimal thermal conditions, the system guarantees a repeatable, high-quality output.

4.3. Discussion and Comparison with Related Works

The results obtained in this study demonstrate significant advancements when compared to recent developments in the field. While Barroso et al. (2022) focused on low-cost automation for laboratory-scale distillation columns, our system successfully scales this automation to a pilot production level (200 L) suitable for SMEs, maintaining a low-cost structure through the use of Arduino and ESP8266.

Regarding control strategy, Kassie et al. (2025) explored complex Fuzzy-PID and GA-PID algorithms. However, our results indicate that a well-tuned industrial PID controller (REX-C100) with auto-tuning capabilities can achieve a comparable stability margin of ±1°C without the high computational overhead required by advanced soft-computing algorithms. This aligns with the findings of Tahir et al. (2025) regarding the effectiveness of optimized control in thermal processes, but our work extends this by integrating a complete IoT monitoring layer.

Furthermore, in terms of safety, the integration of the MQ-3 sensor and automatic cut-off aligns with the safety protocols reviewed by Nair et al. (2024). However, our system improves upon standard safety measures by incorporating real-time mobile alerts via Blynk, reducing the reaction time to potential hazards compared to purely local alarm systems.

4.4. IoT Functionality and Limitations

The IoT integration via Blynk was validated as fully functional. The dashboard (Figure 4) provided real-time data updates with a latency of less than 3 seconds, and remote start/stop commands were executed reliably. During simulated fault testing, the MQ-3 sensor correctly identified a high vapor concentration, triggering the local buzzer/LED and successfully sending a push notification to the operator's smartphone. This modernizes the process, enabling remote supervision and reducing direct labor costs.

Despite these successes, two practical limitations were noted: (1) the initial financial investment for the control components (PID, SSR, sensors) may be a barrier for artisanal producers, and (2) operation and maintenance require a baseline of technical knowledge, potentially necessitating operator training.

5. Conclusion and Future Work

5.1. Conclusion

This study successfully designed and validated an IoT-integrated automated distillation system, addressing the critical inefficiencies of traditional manual alcohol production. By synergizing a REX-C100 PID controller with an ESP8266-based IoT framework, the system achieved all design objectives. Experimental validation confirmed that the automated model maintains the distillation temperature at 78.5°C with a high precision of ±1°C, significantly outperforming manual methods (typically ±5°C).

Quantitatively, the system delivered a 50% reduction in processing time (from 8 to 4 hours) and increased process efficiency from 60% to 90%. Most notably, product consistency improved remarkably to 95%, and the batch capacity was doubled to 200 L without additional labor requirements. The integration of the Blynk platform ensured reliable remote monitoring with a latency of under 3 seconds, while the safety mechanisms effectively detected and responded to simulated ethanol leaks. These results confirm that the proposed system is a cost-effective, safe, and scalable solution for modernizing traditional craft distillation facilities.

5.2. Future work

Building on this successful platform, future work will focus on several key areas for enhancement:

Advanced Control Strategies: Implementing Model Predictive Control (MPC) algorithms on a more powerful microcontroller to better manage the process non-linearities and optimize for multiple objectives (e.g., energy use vs. throughput).

Machine Learning for Optimization: Leveraging the system's data-logging capabilities to train machine learning models that can predict optimal setpoints and heating profiles based on different feedstock characteristics.

Energy Integration: Investigating the integration of heat exchangers for energy recovery from the hot distillate, using it to pre-heat the feedstock and thereby reduce overall energy consumption.

Predictive Maintenance: Expanding the IoT platform's analytics to monitor component performance (e.g., heater duty cycle) and alert operators to potential failures before they occur.

References

Al Shahrani, A. M., Alomar, M. A., Alqahtani, K. N., Basingab, M. S., Sharma, B., & Rizwan, A. (2023). Machine Learning-Enabled Smart Industrial Automation Systems Using Internet of Things. *Sensors*, *23*(1), 324. https://doi.org/doi:10.3390/s23010324

Barroso, L. F., et al. (2022). Low-Cost and Efficient Solution for the Automation of Laboratory Scale Experiments: The Case of Distillation Column. *Technologies*, *10*(2), 42. https://doi.org/doi.org/10.3390/pr10040737

Chaghazardi, Z., & Wüthrich, R. (2022). Design and Deployment of a Data Lake at a Pilot Plant Scale for a Smart Electropolishing Process. *Electrochemical Society Meeting Abstracts 241*(25), 1219–1219. https://doi.org/10.1149/MA2022-01251219mtgabs

Deenadayalan, T., & Deepakraj, E. (2023). IoT-Enabled Ethanol Detection System: A Transformative Stride in Ensuring Food Authenticity. *2023 International Conference on System, Computation, Automation and Networking (ICSCAN)*, 1–5. https://doi.org/10.1109/ICSCAN58655.2023.10395191

Doan, N. T., & Thanh, P. H. (2025). LIQUID LEVEL STABILIZATION USING FUZZY ALGORITHM WITH PLC S7 1200. https://doi.org/doi.org/10.1080/1206212X.2023.2293348

Jimoh, P., & Amire, O. (2024). Fermentation and the production of ethanol from sweet potatoes. https://doi.org/doi.org/10.21203/rs.3.rs-5167676/v1

Kassie, T. D., Geremew, M. S., & Chanie, K. A. (2025). Decoupled level and flow rate control of a two-tank system in beverage production: A comparative analysis of Fuzzy-PID and GA-PID for minimum time operation. *PLoS ONE*, *20*(2), e0317600. https://doi.org/doi.org/10.1371/journal.pone.0317600

Minchala, L. I., Peralta, J., Mata-Quevedo, P., & Rojas, J. (2020). An Approach to Industrial Automation Based on Low-Cost Embedded Platforms and Open Software. *Applied Sciences*, *10*(14), 4696. https://doi.org/doi:10.3390/app10144696

Nair, A., Patil, V., Nair, R., Shetty, A., & Cherian, M. (2024). A review on recent driver safety systems and its emerging solutions. *International Journal of Computers and Applications*, *46*(3), 137–151.

Narender, K., Kareem, D. S., Nasir, Z. A., Prasad, P. H., Charan, T. S., & Naveed, A. (2024). ESP8266-based Industrial Appliances Control System by Blynk Software via WIFI Module. *2024 International Conference on Augmented Reality, Intelligent Systems, and Industrial Automation (ARIIA)*, 1–7. https://doi.org/10.1109/ARIIA63345.2024.11051837

Neha, N., Krishnaprasad, B. S., & Shruthi, M. (2023). Real-time alcohol detection and response system with arduino and MQ-3 sensor integration. *2023 7th International Conference on I-SMAC (IoT in Social, Mobile, Analytics and Cloud)(I-SMAC)*, 1095–1103. https://doi.org/10.1109/I-SMAC58438.2023.10290403

Salehi, H. S., Polat, H. M., de Meyer, F., Houriez, C., Coquelet, C., Vlugt, T. J. H., & Moultos, O. A. (2021). Vapor pressures and vapor phase compositions of choline chloride urea and choline chloride ethylene glycol deep eutectic solvents from molecular simulation. *The Journal of Chemical Physics*, *155*(11). https://doi.org/10.1063/5.0062408

Saroja, K., Stefka Sharon, R., Meena, S., & Chitra, K. (2017). Multi-loop PID controller design for distillation column using firefly algorithm. *International Journal of Engineering and Technology (IJET)*, *9*(2), 1404–1410. https://doi.org/10.21817/ijet/2017/v9i2/170902290

Shiryayeva, O., Suleimenov, B., & Kulakova, Y. (2024). Optimal Design of I-PD and PI-D Industrial Controllers Based on Artificial Intelligence Algorithm. *Algorithms*, *17*(7), 288. https://doi.org/doi:10.3390/a17070288

Sun, C., Tong, Q., Yang, W., & Zhang, W. (2024). DiReDi: Distillation and Reverse Distillation for AIoT Applications. *IEEE Open Journal of the Computer Society*, *5*, 748–760. https://doi.org/10.1109/OJCS.2024.3505195

Tahir, N. M., Zhang, J., & Armstrong, M. (2025). Genetic Algorithm Optimization based Control for Heat Integrated Distillation Column. *2025 22nd International Learning and Technology Conference (L&T)*, *22*, 77–82. https://doi.org/10.1109/LT64002.2025.10940986