Journal of Insights in Basic and Applied Sciences
مجلة رؤى في العلوم الأساسية والتطبيقية
ISSN: 3106-1737
Volume 2, Issue 3, 2026, Pages: 635-643
Journal homepage: https://jibas.com.ly/index.php/jibas/en

An Intelligent Control Framework for Industrial Boilers Using IoT and Self-Tuning PID

Muhammad Ahsan Khalid[1*], Sahar Qayyum[2], Malaikah Shakeel[3], Muhammad Rizwan[4], Zeeshan A. Arfeen[1,5], Junaid Bashir[6]
[1,2,3,4]Department of Electrical Engineering, The Islamia University of Bahawalpur, 63100, Bahawalpur, Pakistan
[5]Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[6]United Business Institute (UBI), Rue de Namur 48, 1000 Bruxelles, Belgium

إطار تحكم ذكي للغلايات الصناعية باستخدام إنترنت الأشياء ومعرف *PID* ذاتي الضبط

محمد احسان خالد [1*]، سحر قيوم [2]، ملائكة شكيل [3]، محمد رضوان [4]، زيشان أ. عارفين [1،5]، جنيد بشير [6]
[1،2،3،4] قسم الهندسة الكهربائية، الجامعة الإسلامية في بهاولبور، 63100، بهاولبور، باكستان
[5]كلية الهندسة الكهربائية، الجامعة التكنولوجية الماليزية، 81310 *UTM* جوهور باهرو، جوهور، ماليزيا.
[6]معهد الأعمال المتحد (*UBI*)، شارع نامور 48، 1000 بروكسل، بلجيكا

*Corresponding author: engineerahsankhalid@gmail.com

Received: June 20, 2026	Accepted: August 25, 2026	Published: September 07, 2026

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Abstract:
The Internet of Things (IoT)-enabled Adaptive PID controller discussed in this study is designed to enhance the safety and performance of industrial boilers. Due to the complex, nonlinear, and time-varying behavior of boiler systems and their high sensitivity to disturbances, conventional PID controllers often suffer from poor stability, degraded tracking performance, and increased fuel consumption. To overcome these limitations, the proposed methodology integrates adaptive control algorithms with IoT-based real-time monitoring to enable online tuning of controller parameters. Key process variables such as temperature, pressure, and water level are measured using sensors and interfaced through an ESP32 microprocessor, providing continuous feedback for control-gain optimization and sustained system stability. The system also supports intelligent automation and predictive maintenance, contributing to reduced operational costs and improved reliability. Experimental validation demonstrates significant improvements in system stability, energy efficiency, and response time when compared with traditional PID control approaches. Overall, the proposed IoT-enabled adaptive control framework offers a practical and cost-effective solution for modern industrial boiler management, aligned with the objectives of Industry 4.0.

Keywords: IoT, Adaptive PID Control, Industrial Boilers, Real Time Monitoring, Industry 4.0

الملخص
صُمم مُتحكم PID التكيفي المُدعم بتقنية إنترنت الأشياء (IoT)، والذي نُوقش في هذه الدراسة، لتعزيز سلامة وأداء الغلايات الصناعية. ونظرًا لسلوك أنظمة الغلايات المُعقد وغير الخطي والمتغير مع الزمن، وحساسيتها العالية للاضطرابات، غالبًا ما تُعاني مُتحكمات PID التقليدية من ضعف الاستقرار، وتدهور أداء التتبع، وزيادة استهلاك الوقود. وللتغلب على هذه القيود، تُدمج المنهجية المُقترحة خوارزميات التحكم التكيفي مع المراقبة الآنية القائمة على إنترنت الأشياء، مما يُتيح ضبط معلمات المُتحكم بشكل فوري. ويتم قياس مُتغيرات العملية الرئيسية، مثل درجة الحرارة والضغط ومستوى الماء، باستخدام

أجهزة استشعار، ويتم ربطها عبر مُعالج دقيق ESP32، مما يُوفر تغذية راجعة مُستمرة لتحسين كسب التحكم والحفاظ على استقرار النظام. كما يدعم النظام الأتمتة الذكية والصيانة التنبؤية، مما يُساهم في خفض تكاليف التشغيل وتحسين الموثوقية. وقد أظهرت التجارب العملية تحسينات كبيرة في استقرار النظام وكفاءة الطاقة ووقت الاستجابة مُقارنةً بأساليب تحكم PID التقليدية. بشكل عام، يوفر إطار التحكم التكيفي المقترح المدعوم بتقنية إنترنت الأشياء حلاً عملياً وفعالاً من حيث التكلفة لإدارة الغلايات الصناعية الحديثة، بما يتماشى مع أهداف الثورة الصناعية الرابعة.

الكلمات المفتاحية: إنترنت الأشياء، التحكم التكيفي PID، الغلايات الصناعية، المراقبة الآنية، الثورة الصناعية الرابعة.

Introduction

Industrial boilers are widely used in power plants and process industries. Maintaining stable temperature and pressure is very important for safe and efficient operation. Traditional PID controllers are commonly used for boiler control, but their performance reduces when system conditions change or disturbances occur. This leads to poor tracking, instability, and high fuel consumption [1].

With the development of IoT technology, real-time monitoring and online control have become possible. By combining IoT with adaptive PID control, controller parameters can be adjusted automatically according to operating conditions. This paper presents an IoT-enabled adaptive PID control system for improving boiler safety and performance [2].

A proportional-integral-derivative (PID) controller is a technique used in most of the well-known controllers, and it has become so popular because both its usage and reliability are quite simple. Fixed PID controllers display poor performance in the case of modern boilers, which have been recognized as complex and time varying in behavior. It is usually suffered from instability, poor set-point tracking, and reduced efficiency [3]. However, making a boiler efficient and reliable as little as possible to the environment is an important aspect of energy generation, manufacturing, and chemical processes [4].

Therefore, the adaptive control strategies can be designed corresponding to the specific objectives above. An adaptive control strategy will provide the flexibility that changes the settings of the controller when the conditions change [5]. In addition to this, IoT opens different avenues such as bringing in remote monitoring of systems, real-time data collection, and predictive analysis of the industrial environment. This means that merging adaptive controls into real-time feedback and data-based decisions will highly contribute to improving boiler performance when IoT integration becomes possible [6].

These three controls are basically applied to three instruments :drum level, flow of steam ,and flow of feed water [7]. All these three have good connections because of long time delays (within hours) between changes in steam drum pressure and temperature. These three variables are also affected by sensor noise and external disturbances caused by load shifts and changes in fuel quality rendering good performance of such controllers unfeasible in many occasions. An IoT-enabled adaptive feedback PID system with real-time operation aims to dynamically tune the PID parameters for improved stability and response [8].

- Making use of Internet of Things sensors to continuously check vital parameters (temperature, flow, pressure, and drum level).
- Through cloud platforms and communication protocols (such MQTT), remote operation and predictive maintenance are made possible. Advanced analytics are supported for defect detection, energy efficiency, and emission reduction [9].

The objective of this study is to develop, deploy, and assess an adaptive PID control system for industrial boilers that is enabled by the Internet of Things. A self-tuning adaptive PID algorithm is to be developed; IoT-based sensing and communication are to be integrated for real-time monitoring; performance is to be validated through modeling, simulation, and experimental testing; and improvements in energy efficiency, reliability, and emission reduction are to be evaluated [10].

An IoT-based sensor network, a control unit (microcontroller/PLC), an IoT gateway for connectivity, and an optional cloud platform for analytics and storage make up the suggested system design. PID gains (k_p, k_i, and k_d) are adjusted in real time utilizing error-driven rules in the adaptive control algorithm's reference-model-based self-tuning mechanism, with stability guaranteed by Lyapunov-based analysis [11]. Control systems design for boiler systems hence increases effectiveness, stability, and sustainability in managing boiler operations; it shows the signals that guide the controller in managing non-linearity, load variations, and disturbances. This work extends the findings of previous research activities through the construction of an entirely IoT-integrated adaptive PID prototype and validation of the same through hands-on testing. This improves the long-term clarity, stability, and consistency of boiler control performance, allowing the controller to effectively manage the nonlinearities, load changes, and disturbances as they relate to the boiler operation. This builds upon previous research work by developing a fully IoT-integrated adaptive PID prototype and validating that prototype in experimental conditions [12].

Literature Review

The main target of energy generation and industrial application as part of operating efficiency in boilers has been that issues have often been largely prevalent owing to variation in energy demand, fuel type, and operating conditions. Such widely used but traditional PID controllers cannot handle complex and changing situations as they are based on fixed settings that do not change. These can be troublesome when things are not constant [13]. In addition, various advanced methods like Model Predictive Control (MPC), cascade PID, fuzzy-PID hybrid, and optimization-based PID tuning have been extended to overcome this limitation.

Although transient responses are improved with MPC and robust control methods and resonances are reduced considerably, the typical budget limits of industrial scenarios make the implementation impractical due to higher computational costs and complex constraints for system modeling. Their parameters adjust in real time to respond to changes in the environment regarding nonlinearities, time delays, and disturbances, while also maintaining the simplicity of PID [14].

From that point on, boiler control has been completely evolved into IoT. It has facilitated predictive maintenance by continuously collecting real-time data through temperature, pressure, and flow sensors. Previous studies have shown that the combination of IoT with conventional controller's increases safety and improves monitoring, as has been shown by LabVIEW-based PID for boiler drum level control. Additionally, recent research shows that optimization algorithms like Ant Colony Optimization (ACO) and Particle Swarm Optimization (PSO) can enhance PID tuning; however, these techniques are typically offline and do not offer real-time flexibility [15]. Nevertheless, these developments, the majority of current solutions are either inflexible or need substantial infrastructure. Dependability and interpretability issues prevent AI-based controllers [16].

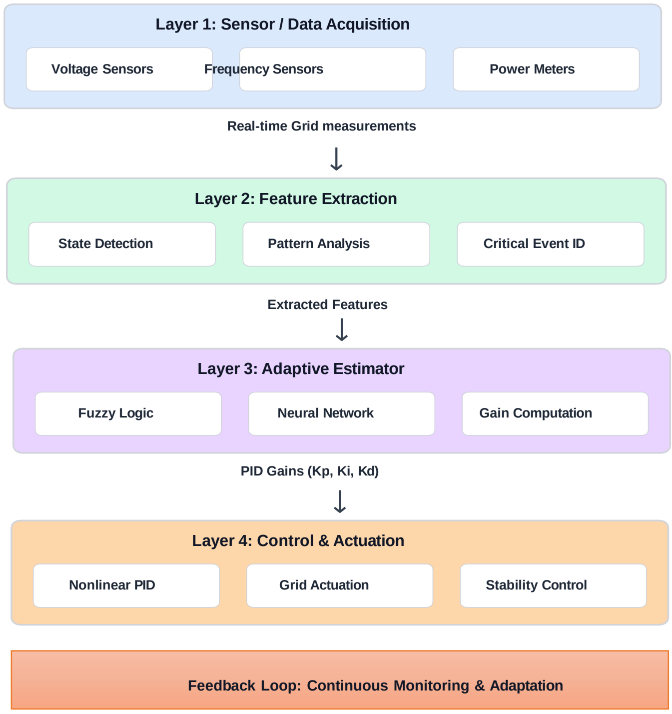

Figure 1: Four-layer adaptive architecture for the Adaptive non-linear PID controller

Though the existing research has focused on MPC, fuzzy-PID systems, and optimization-based tuning approaches, most methods either involve excessive computational power, lack adaptability in real-time, or rely on too expensive industrial infrastructure. Also, the PSO and ACO tuning are offline in nature and thus cannot handle the rapid disturbances associated with boiler systems [17]. Current IoT evolutions primarily focus on monitoring rather than adaptive control. Hence, an evident research gap exists in adopting lightweight, real-time adaptive PID control systems:

- It can adaptively tune their gains online without heavy computations.
- It can integrate seamlessly with IoT platforms.
- It can function on low-cost, embedded hardware ideal for Industry 4.0 applications.
- This study fills these gaps with an Internet of Things (IoT)-enabled Lyapunov-stable adaptive PID framework for real-time boiler operation.

Research Gap

Several studies have focused on PID control for boiler systems. Åström and Hägglund discussed the limitations of conventional PID controllers under varying operating conditions. Adaptive and self-tuning PID controllers have been proposed to improve performance.

Recent research has also explored IoT-based monitoring for industrial processes. IoT allows real-time data collection, remote monitoring, and improved decision-making. However, most existing studies either focus only on IoT monitoring or only on control algorithms.

There is limited work that integrates IoT-based real-time monitoring with adaptive PID tuning specifically for industrial boilers. This gap motivates the proposed work.

Design and Implementation

A boiler system prototype was used to develop and put into action the proposed IoT-enabled adaptive PID controller. To ensure real-time monitoring, flexibility, and remote access, the design included an IoT communication setup, a network of sensors, actuation modules, and a control unit based on a microcontroller.

System Flow and Control Architecture

This was the early process of collecting sensor data, which is to be followed by the next two processes: adaptive PID calculation, actuation, and feedback through the Internet of Things. To maintain stability in various operating conditions, the algorithm keeps varying PID gains (Kp, Ki, and Kd) in relation to the desired and actual values. This closed-loop system keeps all three parameters, temperature, steam pressure, and drum water level, in check.

- The control architecture consists of three functional layers:
- The sensing layer is constantly streaming data from the temperature, pressure, and water level sensors. Control layer: Data processing and actuator control take place in a microcontroller ESP32 which is also involved in the implementation of the adaptive PID algorithm.
- IoT Layer: Remote monitoring, visualization, and predictive diagnostics are made possible by the MQTT protocol, which transfers data to a mobile application dashboard**.**

Hardware Components

ESP32 Microcontroller: chosen due to its low power consumption, integrated Wi-Fi/Bluetooth, and dual-core processing capacity. This serves as the central node or hub for the connectivity and control of IoT [18].

The OLED Display (SSD1306, 128×64) allows the operators to view the system in real-time without requiring any external devices as it provides a local interface for real-time display of the boiler parameters.

- Solenoid valve: Responds to control signals to regulate water inflow to preserve drum level stability [19].
- 4-Channel Relay Module: Offers control and electrical isolation for actuators, such as the pump and burner.
- BMP180 Pressure and Temperature Sensor: For taking the safe operation within threshold limits of temperature of boiler and barometric pressure.
- For process optimization, the water temperature readings are highly accurate, thanks to the DS18B20 Digital Temperature Sensor.
- Burner System: Controls relays switching to simulate heating for prototypes.

Table 1 Hardware components and their specifications

Component	Function	Specification / Feature
ESP32 Microcontroller	Main control and IoT communication	Dual-core processor, Wi-Fi/Bluetooth, 3.3V logic
OLED Display (SSD1306)	Real-time parameter display	128×64 resolution, I2C interface
Solenoid Valve	Water inflow regulation	12V DC, normally closed type
4-Channel Relay Module	Actuator switching	5V input, 10A output per channel

BMP180 Pressure Sensor	Measures boiler pressure	Range: 300–1100 hPa, ±0.02 hPa accuracy
DS18B20 Temperature Sensor	Measures boiler water temperature	Range: -55°C to +125°C, ±0.5°C accuracy
L298 Motor Driver	Motor control	Dual H-Bridge, 2A per channel
Power Supply	Provides operating voltage	12V DC regulated input

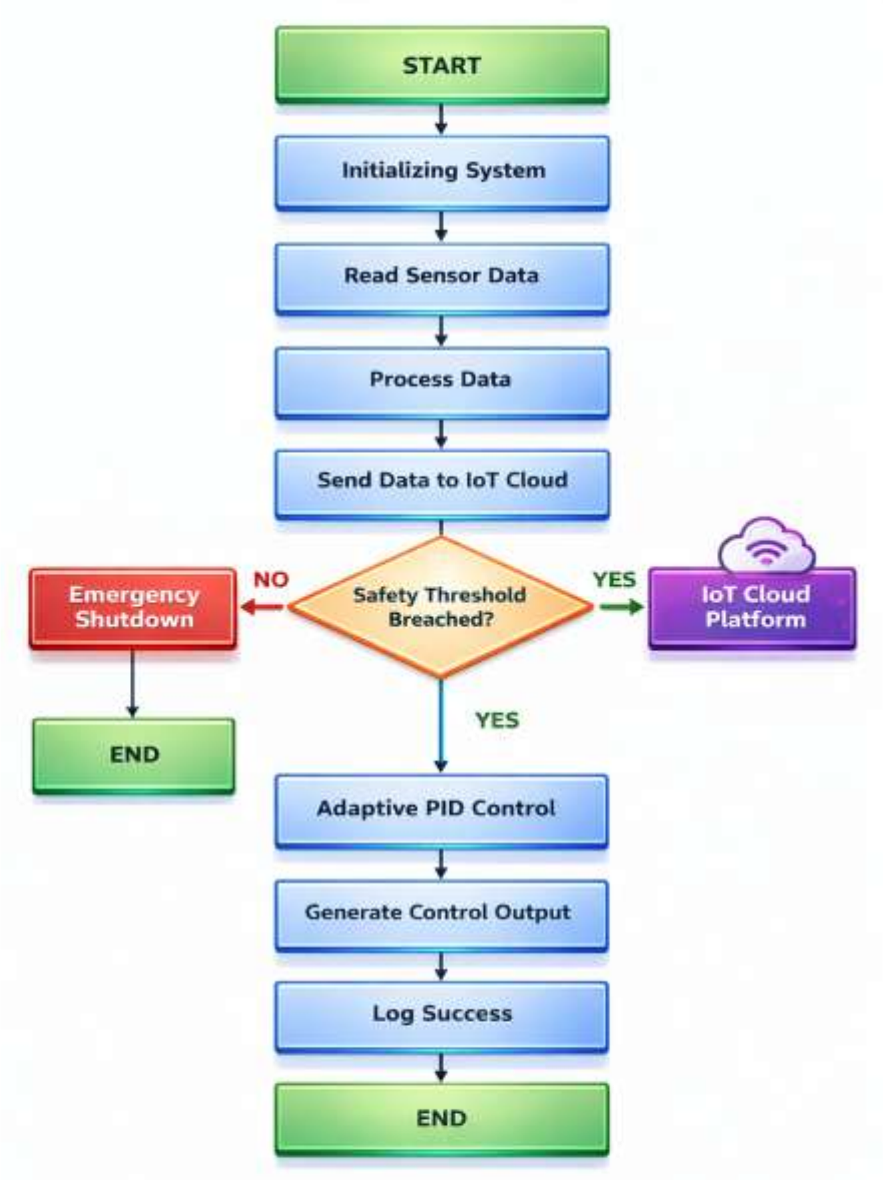

Figure 2: Flowchart of proposed system

Adaptive PID Algorithm

Dynamic PID controller follows a self-tuning rule of updating the controller setting based on the necessary reference values with corresponding real-time sensor readings. Every deviation viewed between the actual and expected responses of the system will automatically tune the controller gains, thus ensuring:

- Fastening response on changes in load. Reduced oscillation caused by delays or disturbance.
- Enhanced economy due to lower fuel consumption and smoother operation conditions.
- The systems designer ensured adaptation with reference and Lyapunov stability criteria for convergence and stability.

Adaptive Law and Stability Analysis

For transparent understanding of proposed controller, adaptive law used for on-line tuning of PID gains is summarized heretofore. The controller updates the parameters in real-time based on the instantaneous tracking error.

$$e(t) = r(t) - y(t) \qquad (1)$$

With r(t) being the output from the reference model and y(t) being the response of the boiler. The gain adaptation mechanism is initiated by an error-gradient update:

$$\dot{K_p} = -\alpha_p e(t)\dot{y}(t), \qquad (2)$$
$$\dot{K_\iota} = -\alpha_i e(t) \qquad (3)$$
$$\dot{K_d} = -\alpha_d \dot{e}(t)\dot{y}(t) \qquad (4)$$

Where α_p,α_i, and α_dare positive adaptation constants.

These rules iteratively reduce error surface and guarantee convergence of the gains toward values that shall improve the stability against disturbances and variations in nonlinearity.

A Lyapunov candidate function ensuring stability is defined as:

$$V = \frac{1}{2}e^2 + \frac{1}{2\alpha_p}\widetilde{K_p}^2 + \frac{1}{2\alpha_i}\widetilde{K_\iota}^2 + \frac{1}{2\alpha_d}\widetilde{K_d}^2, \qquad (5)$$

Where (K_p ̃), (K_i ̃), (K_d ̃)are identification errors.

Substituting the results from the adaptation laws into V̇ results in V̇≤0, ensuring global stability of the closed-loop system.

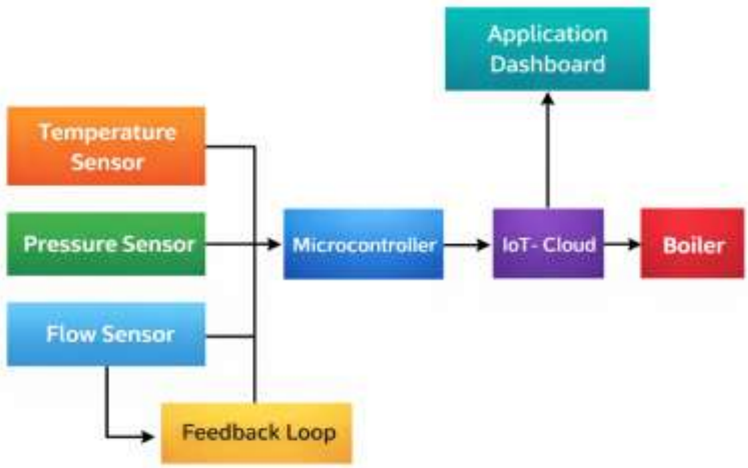

Figure 3: Block diagram of proposed system

IoT Integration

A lightweight messaging protocol, MQTT was employed for proper intercommunication between ESP32 and the mobile app [20]. Real-time monitoring, storing, and analysis are made possible via the transmission of data to a cloud platform. Predictive maintenance is aided by historical data analysis, which spots early indicators of sensor deterioration or process issues [21].

To show data like drum level, steam temperature, and pressure as well as system status alerts, an intuitive mobile dashboard was created. Operators can adjust setpoints and keep an eye on performance remotely without having to visit the location in person.

Prototype Demonstration

A small-scale boiler model was used to test the entire prototype system. Actuators were activated by relays to control burner operation and water flow, while the ESP32 gathered sensor data and carried out adaptive control.

Real-time system feedback was concurrently given by the mobile application and OLED display. Stable boiler operation, less steam pressure variation, and improved flexibility under various simulated loads were all proven by experimental tests.

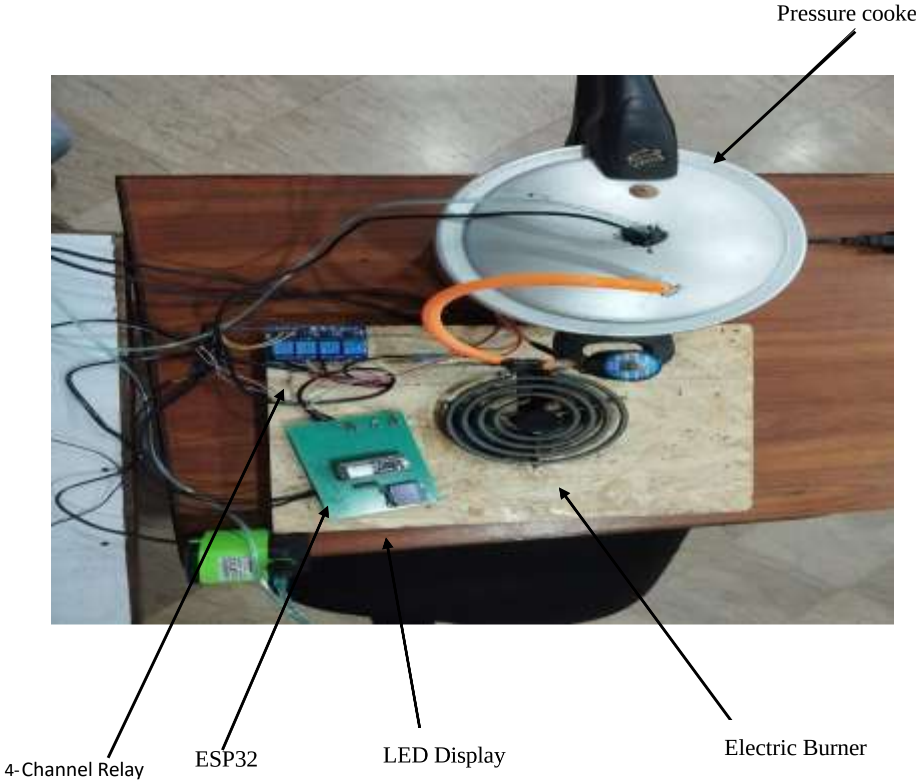

Figure 4: Prototype of the implemented system

Results and Analysis

A small-scale boiler system was used for experimental testing and prototype implementation to validate the suggested IoT-enabled adaptive PID controller. System stability, reaction to disruptions, flexibility under changing loads, and IoT functionality were the main areas of evaluation [22].

Figure 5: LED Monitoring

System Monitoring and Interface

Both local and distant monitoring features were included in the system. Locally, the relay status showed actuator activity, and the OLED display showed the water level, steam temperature, and pressure in real time. The dashboard of the mobile application remotely showed real-time process data sent over MQTT. Operators could adjust set points, see how the system behaved, and get notifications when unusual situations like high temperatures or changes in the water level occurred.

In order to verify that the adaptive PID logic appropriately activated valves, relays, and the burner in accordance with process requirements, LED indicators were used during testing to validate actuation orders**.**

Table 2 Performance Comparison between Conventional PID and IoT Based PID

Parameter	Conventional PID	Adaptive IoT-PID	Improvement (%)
Settling Time (s)	12.8	7.2	43.7% faster
Overshoot (%)	18	6	66.7% reduction
Steady-State Error	2.5%	0.5%	80% reduction
Energy Consumption (W)	92	73	20.6% lower
Response Time (s)	5.3	3.1	41.5% faster

Performance Analysis

Performance analysis by comparing the adaptive PID controller with a fixed-gain PID showed marked improvements in Faster Response: The system's stabilization time after disturbances decreased thereby decreasing the overshoot and settling time**.** Continuous adjustments of the control parameters were made to reduce the oscillation behavior in steam pressure and drum level control [23].

Increased Efficiency

Fuel savings have been realized, and hence less energy is consumed due to improved combustion and water level control. The system gives the best performance or robustness during sudden load variations or fuel disturbances.

Safety and Reliability

Adequate provisions were made to allow for the safe increase of temperature or pressure. IoT connectivity allows for data logging and predictive diagnosis, thereby increasing system value. Given slow trends such as sensor drift or abnormal response patterns, predictive maintenance was primarily based on the analysis of the slow trends shown in the logged data. It was finally concluded that the integration of IoT with adaptive PID enhanced control processes and provided for digital integration, real-time analytics, and remote accessibility-the forward-thinking concepts central to Industry 4.0.

Limitations

It's not likely, but a worthy possibility, that future development involves the mass industrial deployment of such techniques with integrations into ML as part of learning-to-predict adaptation, all under prior longitudinal field measurements for thorough robustness validation across different operational environments.

Conclusion

This research gives an account of how to design, develop, and test IoT-enabled adaptive PID controllers that would be meant to enhance the efficiency of boiler operations. The new proposed method improves stability, efficiency, and safety with IoT technology, which means greater adaptability to the control system. One of the major outcomes of research was to create a self-tuning adaptive PID algorithm that modifies its parameters for real-time changes.

- The provision of Internet of Things-enabled ESP32-based hardware that is scalable and inexpensive for wide adoption.
- Prototype tests based on a boiler model recorded lower energy usage, lesser fluctuations, and faster response times.
- A cloud-based monitoring dashboard was developed for the purpose of remote observation and early detection of possible failures.

This outcome indicated that this will be the approach that will commercially bring about improvement in performance effectiveness for boilers, while also being easily adoptable and at a low price. Additionally, this platform can be used on other industrial processes where punctuality, safety, and monitoring are the major concerns.

Future Work

In the future, the technology application will be inclusive of industrial boilers of high capacity, which will have predictive modifications using Machine learning, and long-term performance will be assessed in real plant environments.

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