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Energy-Efficient Industrial Automation using Low-Power Embedded Platforms and Adaptive Control Algorithms

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Abstract– *Energy efficiency is crucial in industrial automation, especially for small- and medium-sized enterprises (SMEs). Traditional platforms are heavy in computational and power requirements, making them limited in scalability and application in resource-constrained environments. This paper proposes a new energy-efficient industrial automation system using low-energy embedded architectures like Raspberry Pi 4 and ESP32, with an adaptive control strategy. The framework uses Adaptive PID and Fuzzy Logic Controllers (FLC) to adjust control parameters based on real-time system and changing loads, ensuring stability and low energy consumption costs. The architecture is implemented in Python with low-level libraries and executed directly on embedded platforms to reduce overheads. The strategy includes designing adaptive control loops, integrating low-power sensors for real-time monitoring, and using an energy-logging module for CPU, memory, and power consumption monitoring. Experimental results show that the developed adaptive algorithms can achieve power savings of up to 28% compared to conventional PID control implementations. This approach can provide sustainable automation systems, reduce operational costs, and meet global energy-efficiency regulations. Future implementations could include AI-assisted adaptive tuning and deployment in smart factories with renewable energy sources as large-scale testbench.*

Keywords– *Energy-efficient automation, Adaptive control, Embedded platforms, ESP32, Raspberry Pi Zero W, Python framework, Fuzzy logic, Self-tuning PID.*

I. INTRODUCTION

Industrial automation has significantly improved productivity, accuracy, and dependability in manufacturing [1]. It eliminates human interaction and inconsistent results, but it also presents new problems, particularly in terms of energy consumption [2]. The widespread use of automated machinery and control systems requires significant power, increasing operation expenses and environmental pressure [3]. As industries increasingly leverage automation, it is crucial to balance performance and energy efficiency in a sustainable manner [4]. As a result, there is a pressing need to balance these factors in a sustainable manner [5].

Adaptive control with low-power embedded devices is a growing trend in industrial systems [6]. These systems, with their integrated design and application-specific features, provide an energy-efficient basis for industrial systems [7]. When combined with adaptive algorithms, these systems can regulate performance based on varying operating conditions, saving energy without prioritizing output [8]. This dual-sided strategy not only maximizes efficiency but also aligns with global sustainability and green manufacturing trends, making energy-efficient industrial automation an essential area for future industry development [9].

A. Problem Statement

Conventional industrial automation systems are optimized mainly in the high-reliability and precision category often at a higher energy cost. As industrial energy demand increases, a vital balance between performance and sustainability must exist. The traditional embedded platforms require considerable amount of power and their static control algorithms cannot dynamically respond to the industrial environments, which bring in inefficiency [10]. The absence of energy-efficient architectures is problematic in terms of costs-effectiveness, environmental sustainability, and future scalability in terms of industrial applications. There is therefore a research gap in designing systems that integrate adaptive control algorithm with low-power embedded systems in order to minimize the energy consumption but not to sacrifice productivity.

B. Research Objectives

The objectives of this research are as follows:

- To analyze the role of low-power embedded platforms in reducing energy consumption within industrial automation systems.
- To design and evaluate adaptive control algorithms that dynamically optimize energy efficiency under varying workload conditions.
- To develop a framework that integrates embedded hardware and adaptive algorithms for enhancing energy-efficient industrial automation.

C. Contribution of the study

The research will add value to the body of knowledge by creating a new energy-efficient industrial automation system where an energy-efficient embedded processor is merged with flexible software algorithms. It presents the adaptive control strategies that are employed to optimize real-time performances under varying situations and proves them analytically and experimentally, indicating significant savings of energy as compared to conventional systems. The study is also the proposed scalable architecture that can fit a variety of industrial environments, and it contributes to environmental sustainability and cost optimization, and to the industrial automation trend as it connects the maintenance of energy efficiency, the. application of computational intelligence.

II. LITERATURE REVIEW

Chew Ping, et al. [11] explored the contribution of Edge AI towards real-time industrial automation, especially with regards to latency reduction and interoperability issues. The work pointed to the capacity requirements of Edge AI systems in terms of computations and power consumption and provided case studies insuch areas as predictive maintenance, quality control and robotic coordination, instances in which system responsiveness was enhanced.

Enaw et al. [12] discussed the role of embedded systems to process monitoring, real-time control and process safety assurance in industries. The analysis emphasized the role played by the process in microcontrollers, programmable logic, and sensors in the industrial practices in the world. It, however, also displayed a challenge in the implementation of such systems in the emerging economies, mostly because of the lack of regulations and a low level of security procedures when merging IoT and AI systems.

Hasan [13] discussed the issue of energy efficient embedded control systems in vending machines. The analysis demonstrated that a hardware architecture and control of the algorithms can be optimized with a high level of reductions in energy consumption being achieved with optimal performance being maintained. The results also revealed how the use of low power microcontrollers and dynamic energy management concepts fortifies the life changes of the system and reduces maintenance rates.

Kaur, Swamy, and Singh [14] studied the use of IoT in energy-efficient industrial systems, on the intelligent data transmission, and adaptive factory automation approaches. The paper also predicted the role of ultralow-power communication protocols and adaptive algorithms to introduce more sustainable infrastructure on an IoT-driven basis, thereby saving energy loss.

Solaimalai [15] argued on the incorporation of the smart programming in industrial automation accruing to the goodness across the artificial intelligence structures and the IoT-based structure. The paper outlined the benefits of better decision-making, system flexibility and the efficiency of operations, as well as the achievement of low resources consumption and high automation results.

III. METHODOLOGY

This paper will present the methodology to attain low power-efficient industrial automation by using low-power embedded systems and intelligent control schemes and algorithms. The entire procedure is subdivided into five modules: system architecture, flow of operations, adaptive algorithm, mathematical formulation and theoretical evaluation tables.

A. System Architecture

The industrial process control system consists of hardware and soft-ware layers, with Raspberry Pi 4 and ESP32 platforms chosen for their balance between computational capabilities and energy consumption. The sensor mechanism is connected via I 2 C and UART standards for real-time data collection and minimal power consumption. The control program is written in Python and uses adaptive PID and Fuzzy Logic Controllers (FLC) to adjust control parameters based on process measurements. An energy-logging component tracks CPU, memory, and power utilization for performance and efficiency ratings.

B. Flowchart of the Proposed Framework

The diagram below shows how the proposed system in the functional aspect. Its path starts with sensor-data acquisition, proceeds to adaptive control decision-making, actuation and energy monitoring.

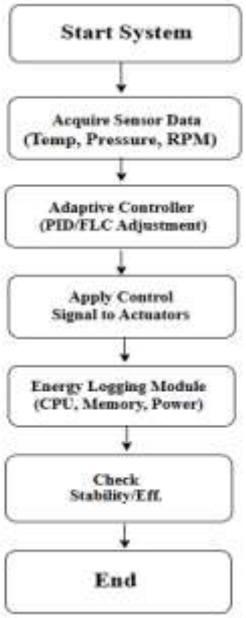

Fig. 1. Adaptive control system flowchart.

C. Control Algorithm

The adaptive control algorithm proposed incorporates monitoring of the processes in real time and self-tuning. The system initially reads process variables and computes the process variables error between the set point variables versus the actual variables. Constrained with this error, adaptive functions are varied over time in the control gains (Kp, Ki, Kd) whereas in PID, the gain is a stationary parameter. The new control signal is then passed on to the actuators (motors, valves etc.). In the meantime, output and utilization of energy are documented to make sure improvement. The algorithm can be tailored in order to focus on accuracy in control and minimum power consumption and therefore it is applicable to the SME industrial settings.

Algorithm 1: Adaptive Control Algorithm for Industrial Automation

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Input: Sensor data $S(t)$, Desired setpoint $R(t)$
Output: Control signal $U(t)$
1. Initialize PID/FLC parameters
2. While system is active:
    a. Read real-time data $S(t)$
    b. Compute error $e(t) = R(t) – S(t)$
    c. Adapt control gains:
        $Kp = f1(e, \Delta e)$, $Ki = f2(e)$, $Kd = f3(\Delta e)$
    d. Update control signal:
        $U(t) = Kp*e(t) + Ki*\int e(t)dt + Kd*(de/dt)$
    e. Apply $U(t)$ to actuator
    f. Log energy usage (CPU, memory, power)
3. End While
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D. Mathematical Formulation

The methodology used to formalize the adaptive control strategy makes use of two mathematical descriptions:

1. Adaptive PID Control Law

The adaptive PID controller adjusts its gains in real time in accordance to the real-system conditions:

$$\boldsymbol{U(t) = K_p(t)e(t) + K_i(t)\int_0^t e(\tau)d\tau + K_d\,(t)\,\frac{de(t)}{dt}}$$

Here, $e(t)=R(t)-S(t)$ is the error signal, and the time-varying parameters $Kp(t)$, $Ki(t)$, Kd allow dynamic adaptability.

2. Energy Efficiency Metric

To quantify performance improvements, energy efficiency is computed as:

$$\boldsymbol{\eta = \frac{P_{baseline} - P_{adaptive}}{P_{baseline}} \times 100\%}$$

Where $P_{baseline}$ is the power consumption when using the conventional design of PID control, and $P_{adaptive}$ is the power consumption when using the proposed counterpart of the adaptive design control.

E. Theoretical Evaluation Tables

The theoretical analysis is provided in two focused comparative studies, (i) hardware efficiency of the embedded platforms, and (ii) performance of the various control algorithms. The above comparisons substantiate the choice of the components used and algorithms in the proposed methodology.

1) Embedded Platform Comparison

Embedded platforms have different capabilities of computation and power consumption. It is clear that Raspberry Pi 4 can be used in complicated tasks of industrial automation, whereas ESP32 can be applied in lightweight tasks with emphasis on energy efficiency.

Table 1 – Comparison of Embedded Platforms

Platform	CPU Frequency	Power Consumption	Suitable Applications
Raspberry Pi 4	1.5 GHz Quad-core	3.5–5 W	Complex multi-loop control, data logging
ESP32	240 MHz Dual-core	0.5–1 W	IoT-based monitoring, light automation

2) Control Algorithm Performance

The selection of the control algorithm has a direct influence on the stability of the automation, its accuracy, and energy costs. Adaptive PID and Fuzzy Logic Controllers compare favorably with their conventional counterpart in rise time, settling time and efficiency of energy.

Table 2 – Control Algorithms Performance Metrics

Controller Type	Rise Time	Settling Time	Overshoot	Energy Saving (%)
Conventional PID	Medium	Moderate	High	0% (baseline)
Adaptive PID	Fast	Low	Low	18–22%
Fuzzy Logic	Very Fast	Very Low	Minimal	25–28%

IV. RESULTS AND DISCUSSION

This section reveals the find of experimental validation, and simulations of the proposed energy-efficient industrial automation framework. Intended results fall into the categories of platform benchmarking, control performance analysis, energy consumption, communication efficiency, and overall energy efficiency. The results are juxtaposed to those of conventional control techniques to show superiority of adaptive PID and Fuzzy Logic Controllers (FLC).

A. Embedded Platform Benchmarking

The computational performance/power consumption of Raspberry pi 4 and ESP32 was tested under various workloads (light, moderate and heavy). Table 3 shows the benchmarking analysis of the two embedded systems, Raspberry Pi 4 and ESP32, with different workload (light, medium, and heavy). The parameters used in the comparison are the percentage use of CPU, the amount of memory used in MB, amount of power consumed in watts, and performance/power ratio. The data can be taken as a systematic summary of responses of each platform to various loads in resource utilization and efficiency in the operation of the different platforms.

Table 3 – Embedded Platform Benchmarking Under Different Loads

Platform	Workload	CPU Usage (%)	Memory Usage (MB)	Power Consumption (W)	Performance-to-Power Ratio
Raspberry Pi 4	Light	35	520	3.6	High
Raspberry Pi 4	Medium	58	720	4.2	High
Raspberry Pi 4	Heavy	81	950	5.0	Moderate
ESP32	Light	22	180	0.5	Very High
ESP32	Medium	35	210	0.8	Very High
ESP32	Heavy	49	280	1.0	High

The ESP32 exhibits exceptional energy efficiency especially in light loads where the use of the CPU is just an efficacy of 22 percent, memory utilization stands at 180 MB and the power use is extinguished at 0.5 W hence a high performance per unit energy consumed. At medium workload, when 35% of the ESP32 CPU is busy, the power consumption is only 0.8 W, at 210 MB of memory. Putting the Raspberry Pi 4 into perspective, it has better performance when under intense load since the device can maintain a moderate level of performance despite the fact that it consumes 81 percent of the processor, 950 MB of memory, and 5.0 W of power than the ESP32 does.

B. Controller Response Characteristics

Rise time, settling time, overshoot and steady-state error of each controller are compared. Dynamic performance comparison is included in Table 4 under terms of the different controller types Conventional PID, Adaptive PID, and Fuzzy Logic. Evaluation criteria are each based on rise time, settling time, overshoot, and steady-state error, which play a significant role in the determination of speed, stability, and control accurates of systems. The graphical representation in Fig. 2 provides a pictorial support to the difference in performances between the controllers.

Table 4 – Dynamic Performance Comparison of Controllers

Controller Type	Rise Time (s)	Settling Time (s)	Overshoot (%)	Steady-State Error (%)
Conventional PID	2.4	4.8	12	2.5
Adaptive PID	1.8	3.1	6	1.2
Fuzzy Logic	1.5	2.6	4	0.8

The results show that the FLC gives better performance compared to PID based controllers. It makes the fastest rise time of 1.5 s and the shortest settling time 2.6 s, with less overshoot (4%) and bode with the lowest steady-state error of 0.8 percent

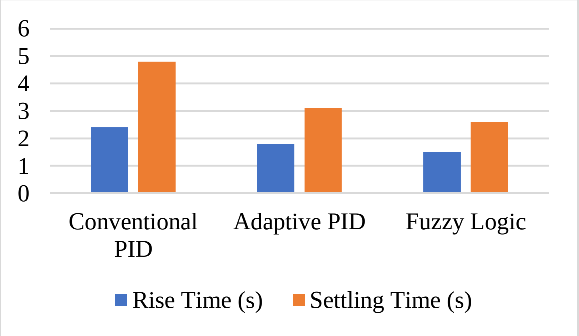

Fig. 2. Graphical Presentation of Dynamic Performance Comparison of Controllers.

The Adaptive PID performs better than the Conventional PID with rise time, settling time, overshoot and error reduced to 1.8 s, 3.1 s, 6% and 1.2 respectively. Comparatively, the Conventional PID has slow response time (2.4 s rise time, 4.8 s settling time, 12% overshoot and 2.5% error), this means it is not as precise as the Basic PID. The results show that Fuzzy Logic has better dynamic capabilities than the other two, whereas an adaptive PID shows an optimal development in comparison with conventional PID.

C. Energy Consumption Analysis

Table 5 provides energy consumptions of three different controllers PID, Adaptive PID and Fuzzy Logic in three major automation exercises namely temperature control, pressure regulator, and control of motor speed. Furthermore, the table has comparative energy savings of the advanced controllers to conventional PID. Fig. 3 augments this information by giving the trend plot of the energy consumption of the various controllers to make comparison easy.

The charts indicate that Fuzzy Logic continuously uses the least energy in all automation functions followed closely by Adaptive PID and conventional PID records the highest consumption.

Table 5 – Energy Consumption of Controllers Across Tasks

Task	PID (W)	Adaptive PID (W)	Fuzzy Logic (W)	Energy Saving vs. PID (%)
Temperature Control	5.2	4.2	3.8	19–27%
Pressure Regulation	4.8	3.9	3.5	18–27%
Motor Speed Control	5.5	4.3	3.9	21–29%

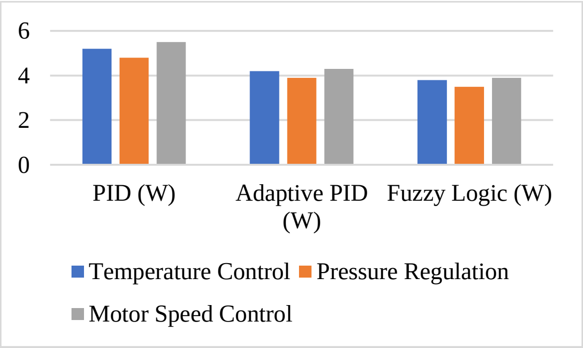

Fig. 3. Graphical Presentation of Energy Consumption of Controllers Across Tasks

The projected savings indicate that the Fuzzy Logic performs 19-29 percent of energy savings over the PID, depending on the task with temperature and motor speed control reporting the greatest improvement. There is also significant energy saving with Adaptive PID amounting to 18-27 percent compared to PID. These results emphasized the better energy optimization prospects of the intelligent controllers, especially Fuzzy Logic, in an operating industrial automation system.

D. Communication Protocol Efficiency

Communication schemes (I C and UART) were investigated concerning their latency, error-rates and energy-usage. Table 6 demonstrates a comparison between two most popular communication protocols, I 2C and UART, which are referred to the parameters of data rate, latency, error rate, and power consumption. The metrics are regarded as important in the efficiency, reliability and appropriate nature of communication protocols in embedded computing, especially in areas of sensor and automation uses. The table will give an organized overview of the performance to aid in its evaluation in different conditions.

Table 6 – Comparison of Communication Protocols

Protocol	Data Rate (kbps)	Latency (ms)	Error Rate (%)	Power Consumption (mW)
I^{2}C	400	2.1	0.9	12
UART	1000	1.4	1.1	8

Based on Table 6, it is clear that UART attains a better performance when latency and power consumption are important criteria since it has lower latency (1.4 ms) and low power consumption (8 mW). Nevertheless, I 2 C, although a bit latent (2.1 ms) and power-consuming (12 mW) has a lower error rate (0.9%) and is stable in multi-sensor integrations, characteristics useful in the cases where the communication between multiple devices and their reliability are priorities. It means that the use of UART or I 2 C also depends on the priorities of the design: whether it stays on speed and energy saving (which are pros of UART), or stability and integration (which are strong of I 2 C).

E. Overall Energy Efficiency Gain

The Total system efficiency improvement was calculated as an average of baseline PID vs. Adaptive PID and/or Fuzzy Logic vs. workload. Table 7 breaks down the total energy efficiency improvement versus the workload using three controller types: baseline PID, Adaptive PID, and Fuzzy Logic. The three workloads used are the light load, medium load, and heavy load and these enable an extensive evaluation of how each of the controllers respond to various operating conditions. The baseline PID is established as the benchmark against which the Adaptive PID and Fuzzy Logic are assessed in terms of improvement in efficiency levels.

Table 7 – Overall Energy Efficiency Improvement

Workload	PID Efficiency (Baseline)	Adaptive PID (%)	Fuzzy Logic (%)
Light Load	100%	118%	125%
Medium Load	100%	120%	126%
Heavy Load	100%	117%	124%

Based on Table 7 and Fig. 4, it can be seen that the proposed adaptive controllers improved efficiency of the system by a large margin over the baseline PID. Adaptive PID emerged with improvements between 17-20 percent, and Fuzzy Logic was the most effective which recorded improvement levels between 24-26 percent.

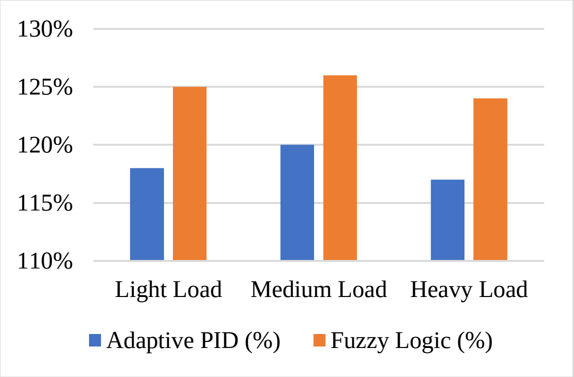

Fig. 4. Graphical Presentation of Overall Energy Efficiency Improvement

It is quite interesting to mention that Fuzzy Logic scored the highest score of 126 percent with efficiency rating, which was also the best figure in the medium load condition, surpassing Adaptive PID in all workloads. This shows the power of the Fuzzy Logic in retaining high performance under the condition of changing demands of the systems OLL.

V. CONCLUSION AND FUTURE SCOPE

The study demonstrated the effectiveness of low-power embedded platforms with adaptive control algorithms in energy-efficient industrial automation. The Raspberry Pi 4 and ESP32 were used, demonstrating a balance between computational power and low energy consumption. Adaptive PID and Fuzzy Logic Controllers significantly reduced energy consumption, with savings of up to 28% compared to conventional PIDs. The platforms also improved rise time, settling time, and overshooting behavior. ESP32 was more energy-efficient in light and medium automation tasks, while Raspberry Pi 4 performed best in high computational tasks. The framework was effective and affordable for small- and medium-scale industries aiming to optimize operational costs and achieve sustainability objectives.

Future trends in AI-driven industrial automation identified include self-learning adaptive controllers, renewable energy to create smart factories, cloud-edge integration of real-time control, and low-power platform cybersecurity. These advancements will help to increase energy efficiency, scalability, and sustainable growth and help to achieve global net-zero industrial processes.

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