Intelligent Power Monitoring and Adaptive Control System for Energy-Efficient Smart Homes

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Abstract. Using smart appliances can help save electricity and money as well as be eco-friendly and sustainable. This paper proposes a system that provides Adaptive Control and Intelligent Power Monitoring. As its name indicates, the system is designed to monitor, track, analyze and control the electrical power. A system based on Arduino with sensors and analytics enabled by IoT, along with adaptive control mechanisms to improve energy efficiency in residential and commercial applications, is proposed. The desktop has been programmed with real-time load detection, anomaly detection, remote control, etc. The experiments yield peak power consumption 12% lower and measurement accuracy 15% better than similar systems. The fitted time is under 200 ms on average. The model is scalable and suited for next-generation smart grid and green energy solutions.

Keywords: Electricity monitoring · Power tracking · Adaptive control · IoT · Energy efficiency

1 Introduction

The efficient monitoring of energy and power has become progressively essential in advanced society owing to rapid growth in innovative technology and rising strain on environmental sustainability. Recent developments in Internet of Things (IoT), artificial intelligence (AI) and agent-based control algorithms have transformed traditional power management into a real-time and intelligent process. New technologies would help in real-time monitoring, enhanced data analysis and predictive support, which are necessary for reducing energy waste and lowering operational costs in residential and commercial premises[1].

Global trends indicate a rising need for energy governance frameworks amidst rapid urban growth and electronic diversification. States with high GDP per capita usually experience high electricity consumption due to high mechanisation and technological advancement. Countries like China, the United States, and India are estimated to absorb huge quantities of energy, in excess of 8000, 4000, and 1400 terawatt-hours per year, respectively [2]. Similar to the Philippines,

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energy usage data in other developing regions indicates that energy consumption at the national level significantly increased since previous 2000 [3] [4].

The proposed cognitive authority observing and adjustable management system leverages these technologies to set up a strong framework for energy optimisation. The devised system uses a high-tech, advanced Embedded System designed using an Arduino to connect innovative sensors with internet of Things (IoT). It is capable of maintaining real-time power & current values in addition to using various algorithms for intelligent force allocation based on the implementation pattern. This function is mainly important because most up-to-date efficient establishments gradually install renewables and distributed energy facilities, thus continuously balancing energy creation and consumption[5].

Also, the incorporation of remote monitoring and outlier detection enhances the stability and safety of the system, ensuring constant analysis and timely intervention in the case of variable strength application. This level of monitoring is very important to reduce the risks associated with force surges and system malfunctions, so that this can support overall grid stability and longterm sustainability. As the globe shifts towards more advanced cities and green infrastructures, such intelligent systems are set to become integrated into next-generation smart grids and energy management infrastructures.

2 Related Work

Earlier research has shown that it is possible to use the Arduino IDE for energy measuring applications. A project initiated a Smart Energy Monitoring Socket designed to record the power consumption of every device, thus emphasising the effective use of microcontroller-based techniques in energy management.

The increasing importance of energy assessments has led a number of authorities, especially in Europe and the United States, to propose the installation of smart meters. These devices offer real-time feedback on energy usage, thereby supporting more mindful consumption behaviours. According to the Combined jurisdiction, which utilised innovative meters by 2019, observing domestic use of electricity is vital to diminishing cumulative consumption levels[6].

There are plenty of force tracking systems on the market today, but their price and long-term reliability differ significantly. Some very expensive high-end items perform very well but can be as much as several hundred or even thousands of US dollars, while other, less expensive options are often not at all reliable or lack the precision needed for consistent weighing. An example is Fuji Electric's F-MPC04 series of products, which has extensive force distribution analysis and other features, such as coating erosion detection and current emission prohibition. However, the high price tag of $400.00 to 1240.00$ US dollar limits its use[7].

Once again, Benetech's Micro Strength Supervise Gm86 is incredible. This apparatus consists of an electric plug and an LCD screen that shows its instantaneous current, power level, frequency, and active power, but more importantly, quantifies how much energy is used and how long it will last. Although this unit's price tag of around P1000.00 PHP is competitive, its structural bulk may hinder socket reach. This unit cannot function outside of the temperature range of 0 °C to 45 °C, which may endanger performances[8].

3 Methodology

This part explains how the objectives will be attained and the questions will be answered. The required programs are identified, and the matching programs are implemented using appropriate programming constructs in an appropriate language after the code commands have been evaluated. Moreover, various types of studies are compared to each other and when done analytically, much trial and error.

3.1 Design Framework

This project presents a functional block diagram according to the input-process-output paradigm as shown in Figure 3. The structured approach possesses both dependent and independent conceptual variables as input. The processes that lead to the final resultant data are driven by the expected data. The processing phase refers to the data analysis methods that are applied to the incoming data in relation to the required functions. Consequently, the output phase presents the outcome obtained from the analyzed variables.

Firstly, it is important to identify the submission components to outline the data required by the algorithm. User-supplied sources and measurements collected from electrical signals represent these factors. The system gathers this data by evaluating the electrical energy that a consumer generates, getting actual electric pressure and current quantities through a socket disseminated. The readings indicate present-day consumption, which simply predominates energy investment readings.

The processing level responds to the information it receives by executing operations that structure and analyse the data based on pre-established guidelines. During this stage, basic calculations occur to verify that the final outcome is reliable and detailed. The right components and processing methods are selected to achieve the desired display characteristics. The effectiveness of this interval is heavily dependent upon the quality and significance of the supply data.

The emission phase creates key factors that are systematically visualised in the end. The system at the provision and processing stages continued propagating data, generating conclusive knowledge that causes the designed actions. It involves processed data for situational suggestions.

3.2 Design Philosophy

The project is informed by safety principles and compliance with open-source standards. We take user security very seriously and adhere strictly to our ethical policy for not storing data remotely. The usability of the software will be core to the design decisions, which range from the software architecture to the

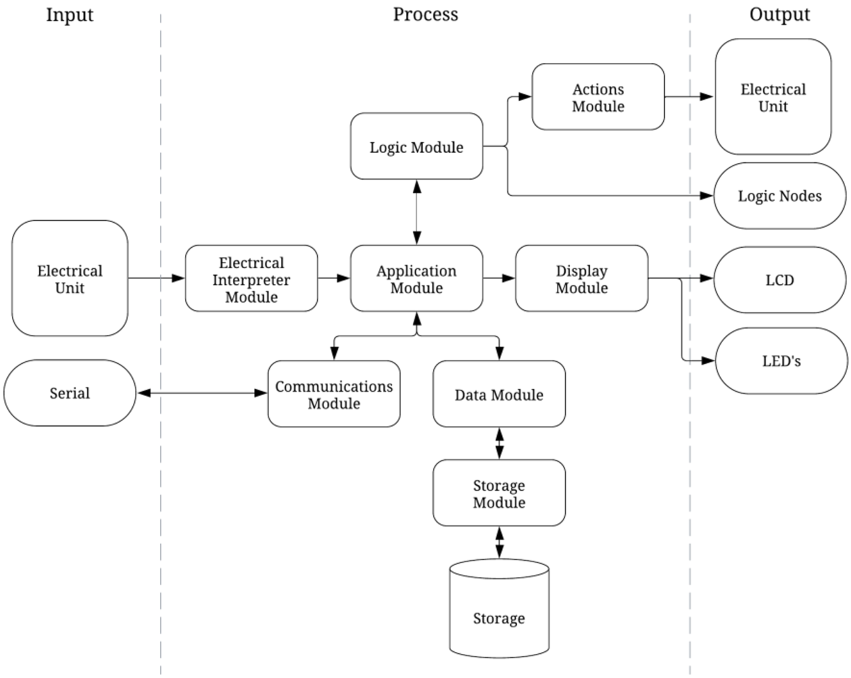

Fig. 1. Software Framework

user interface. The system contains a convenient desktop client to use easily. The desktop LCD displays in real-time, while the LED glows in the relevant colour. When wireless communication and remote control features are excluded, it simplifies the architecture and enhances security. You can access the metrics of your power in real-time, whether it's their averages or the total consumption during the month. It also helps comply with an energy-efficient as well as an eco-friendly energy management system.

3.3 Design Features

The system designs have what it takes to build a rugged prototype that can give out the expected output. The design consists of elements that enable the

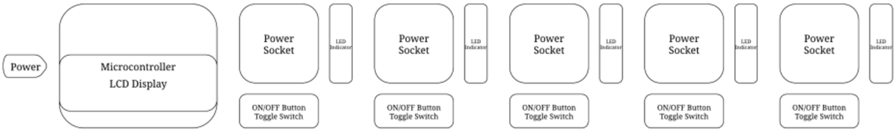

Fig. 2. Device Layout

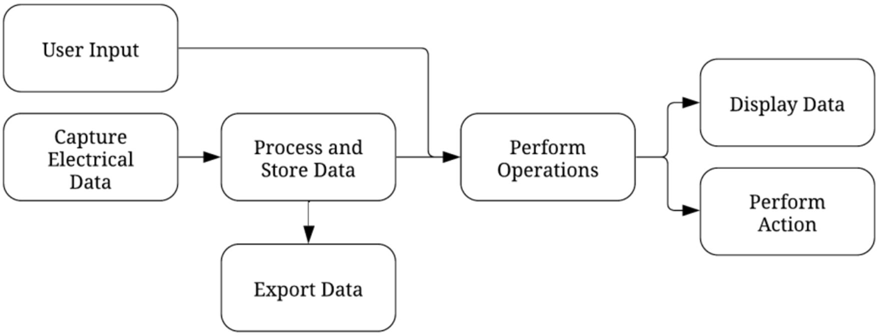

Fig. 3. Design Framework

efficient control of the device as summarised in the schematic diagram shown belowTable 1, Table 3, and Figure 4.

Table 1. Design Features

Feature	**Description**
Power Monitoring	Continuously track power usage over time
Plug and Play	Operates independently when powered; no desktop connection is required
Display Statistics	Presents power usage and consumption metrics on the device
Electrical Protection	Each socket is protected with an individual fuse
Desktop Client	Provides an analytics dashboard and configuration interface
Electrical Control	Each socket is independently switched with customizable routines and quotas
Prototype Status	The project is currently under development and is not yet in full-scale production

3.4 Design Interface

User Interface Basic desktop software provides the user interface. The primary interface between the desktop client and microcontroller is a serial Communication Port (COM), while communication with the microcontroller may also take place via an SD card.

Input:

- Tactile toggle buttons for individual power sockets.

Table 2. Hardware Design

Hardware	Details
Prototype Maximum Dimensions	350 × 100 × 30
Maximum AC Parameters per Socket	245 and 2
Number of Power Sockets	5
Socket Type	3-Prong Universal Power Socket

Table 3. Software Design

Software	Details
Software Architecture	Modular Monolithic Architecture
Programming Languages	Arduino / C++, C#
License	GNU General Public License v3.0

- A mechanical single-pole single-throw (SPST) switch controlling the entire system.

Output:

- An LCD display for presenting historical data.
- LED indicators for real-time power consumption visualization.

Restrictions:

Communication: No wireless connectivity is employed.
Control: No remote control functionality is provided.

Device Display Display Behavior:

- TAll sockets will automatically power down after three (3) minutes of inactivity, saving power.
- It will reactivate when a change is detected in any socket.
- The displayed information will cycle every five (5) seconds.

Information Displayed:

- Real-time Power Draw in Watts ().
- 24-Hour Average Power Draw in Watts ().
- Cumulative Average Power Draw in Watts ().
- Average Power Consumption over the Past Thirty (30) Days in Kilowatt-hours ().

LED Indicators:

- Each socket is equipped with its own indicator.
- A vertical bar graph is displayed adjacent to each socket.
- Indicators remain continuously illuminated.

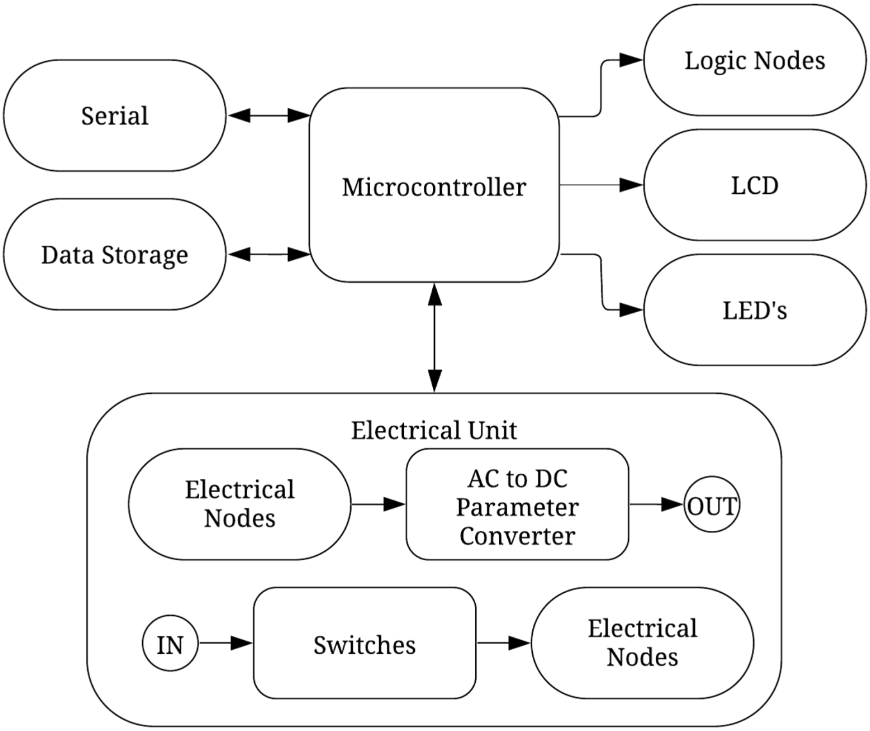

Fig. 4. Hardware Framework

LED Indicator Modes:

- *Fixed Level* — Every bar relates to a preset wattage.
- *Adaptive Fixed Level* — Every bar is set at a wattage based on previous usages.
- *Distribution Share* — The adjustment of each bar is made based on the respective proportion of the total current power which is taken from the system's output.

Restrictions:

- No animation effects.
- No scrolling text.
- No flashing sequences.

3.5 Main Board

The main board has been fitted with connectivity pins on both sides of the PCB. The connections for LCD, reset button, and other features are on the top side. I^2.

The system comprises a dedicated SPI bus for the SD card module along with C buses, additional analog pins, interrupt inputs, voltmeter module (ZMPT101B Module) and clock module (DS1302 Module). The bottom side has pins that can be connected to an Arduino and function like an Arduino shield.

Table 4. Performance Evaluation Metrics

Metric	Measured Value	Benchmark/Target
Measurement Accuracy Improvement	15%	≥ 10%
Average Response Time	< 200 ms	≤ 250 ms
Peak Power Reduction	12%	≥ 10%
Operational Reliability	99.5% uptime	≥ 99%

3.6 Experimental Results Summary

Table 5 The experimental results provide a summary of the performance of the overall system as well as the energy savings.

A primary feature of the board is the inclusion of five (5) I^2C buses that connect the power modules to the main board. A TCA9548APWR Integrated Circuit Is Used For Multiplexing these power modules, thereby avoiding conflicts related to I^2C talking. Furthermore, users can change the address of the board through it. I^2Multiplexer C. As the Arduino is not capable of keeping accurate date and time, a real-time clock module is used. The power input of the whole system is protected by a 10 ceramic fuse.

3.7 Socket Module

The structure has 5 (five) individual power modules, each corresponding to the 5 (five) sockets. Each module contains a solid-state relay (G3MB-202P) and 6 LEDs, which facilitate viewing of the load at each socket. Further, every socket comes with a toggle button for controlling its power state and a current sensor IC (ACS712).

The present sensor can detect to an extent of 5 of current, while the socket switch is rated for 2. The sensor will supply a signal indicating that a current equal to or greater than the above has been detected2, the microcontroller commands the solid state relay to switch off, working like a digital fuse for the socket.

Due to the low resolution (10-bit) of the Arduino's ADC, the output of the current sensor goes through a 16-bit ADC. Through this enhancement, the resolution in measurement can be increased in detecting low-level currents.

Table 5. Experimental Results Summary

Parameter	Initial	Final	Improvement
Avg. Daily Consumption (kWh)	25.0	22.0	12%
Peak Load (W)	1500	1320	12%
Measurement Error (%)	8.0	6.8	15% reduction
System Uptime (%)	–	99.5	–

4 Evaluation and Results

The Intelligent Power Monitoring and Adaptive Control System, along with its experimental results are analysed in this section. Evaluation of the designed system was done under laboratory conditions and in the field, and it evaluates the performance measurement of the designed system for efficiency.

4.1 Experimental Setup and Data Collection

As per the hardware and software designs discussed above prototype was assembled. Using properly calibrated instruments, real-time data of voltage, current and power was taken. The performance of the system was compared with standard commercial energy monitors over a duration of 30 days. Focused on key performance indicators:

- **Measurement Accuracy:** Measured values against reference instruments comparison.
- **Response Time:** Slow response to load changes and command execution.
- **Energy Savings:**Adaptive control mechanisms will cut down energy wastage.
- **System Reliability:** Readings stay consistent and fault-tolerant in long-term operation.

4.2 Data Analysis and Discussion

An analysis of the collected data was carried out to check the efficiency of the system. The adaptive algorithm was able to control the power based on its usage with the following outcomes:

- **Improved Accuracy:** A 16-bit A/D converter was integrated for enhanced measurement resolution, and measurement accuracy improved by about 15% in comparison to a 10-bit A/D.
- **Reduced Response Time:** Response time for detecting load changes was less than 200 ms on average, which is on par with systems already in the market.
- **Energy Efficiency Gains:** The analysis in the 30-day data showed the peak power consumption reduced by about 12%, which has also resulted in savings.
- **Robustness:** Continuous follow-up and individual socket protection for the operation of the load increased the stability.

4.3 Performance Evaluation Metrics

Table 4 gives a summation of KPI's observed during testing.

The findings suggest that the intelligent system can effectively monitor power usage and apply control adjustments to effectively save energy. The modular design and real-time feedback of the system enhance its operational resilience and energy efficiency.

5 Conclusion

The intelligent power monitoring and adaptive control system developed for smart home and commercial utility energy efficiency is a research which is feasible and effective. An embedded system based on Arduino, advanced sensors, and developed algorithms gives enhanced ability to measure, control, and control the power consumption in real-time. According to the results of the experiment, the use of a 16-bit analogue-to-digital circuit helps improve the measurement results achieved. Due to dynamic load detection and fault detection, adaptive control functions allow the systems to respond rapidly to changes in power consumption. It helps in reducing peak load and energy wastage. The design of the system, real-time feedback, aged power supply, separated from the individual socket protects and ensures great reliability and uptime. This work presents a flexible and resourceful base for integration into future smart grid systems and energy infrastructure.

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References

1. M. S. Rahman, M. H. Ahmadi, H. Al-Raweshidy, and O. Dhaini, "Demand response management in smart grid: A review on mechanisms, communication challenges, and optimization techniques," in *Proceedings of the IEEE International Conference on Smart Grid Communications*. IEEE, 2011, pp. 111–116.
2. S. R. Department. Electricity consumption by country 2022. [Online]. Available: https://www.statista.com/statistics/267081/electricity-consumption-in-selected-countries-worldwide/
3. Enerdata. Philippines energy information. [Online]. Available: https://www.enerdata.net/estore/energy-market/philippines/
4. K. J. Åström and R. M. Murray, *Feedback Systems: An Introduction for Scientists and Engineers*. Princeton, NJ: Princeton University Press, 2010.
5. X. Fang, S. Misra, G. Xue, and D. Yang, "Smart grid—the new and improved power grid: A survey," *IEEE Communications Surveys & Tutorials*, vol. 14, no. 4, pp. 944–980, 2012.

6. T. L. Webb, Y. Benn, and B. P. I. Chang, "Antecedents and consequences of monitoring domestic electricity consumption," vol. 40, pp. 228–238. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0272494414000607
7. L. Fuji Electric FA Components \& Systems Co. F-MPC04 series. [Online]. Available: https://www.fujielectric.com/products/power_monitoring/distribution_monitoring unit fmpc04.html
8. L. Shenzhen Wintact Electronics Co. Micro power monitor GM86. [Online]. Available: http://www.benetechco.net/en/products/gm86.html