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Development of an Intelligent Mechatronic System for Optimizing Household Energy Consumption

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Abstract: This paper presents the design and development of an intelligent mechatronic system aimed at optimizing household energy consumption. The growing demand for electricity and the need for sustainable energy use have increased interest in smart home technologies. The proposed system integrates sensors, a microcontroller, relay switches, and a Wi-Fi module to monitor and control electrical appliances in real time. It collects data on energy usage and applies programmed logic to reduce unnecessary power consumption by automatically turning off idle devices. Users can also monitor and manage their energy usage remotely through a mobile application. The system is designed to be low-cost, user-friendly, and easily expandable for larger residential setups. Experimental results show up to 25% reduction in electricity usage during peak hours. This solution offers a promising approach to energy efficiency and cost savings in domestic environments, making it highly applicable for modern smart homes seeking sustainable and intelligent energy management systems.

Keywords: Intelligent mechatronic system, energy optimization, household energy consumption, smart home, energy efficiency, Arduino, IoT, real-time monitoring, energy management, automation.

Introduction. In recent years, the global demand for electrical energy has been rising steadily due to rapid urbanization, population growth, and increased use of household electrical appliances. As a result, energy conservation has become a critical issue, both for environmental sustainability and for reducing household energy expenses. Traditional households often lack effective systems for monitoring and managing electricity usage, which leads to energy wastage, especially during peak hours or when devices are left running unnecessarily [1].

To address these challenges, intelligent energy management systems are becoming increasingly popular. Mechatronic systems, which combine mechanical, electronic, control, and computer engineering, offer an integrated solution to this problem. By using smart sensors, microcontrollers, and control algorithms, these systems can automatically monitor and manage energy consumption in real time. This integration not only enhances the efficiency of energy use but also contributes to the creation of smart homes, where automation plays a vital role in convenience and sustainability.

The development of an intelligent mechatronic system for household energy optimization focuses on real-time data collection, decision-making based on user-defined parameters, and automated control of electrical appliances. The system also provides users with access to usage data via a user-friendly interface, enabling informed decisions about energy usage. Furthermore, with the inclusion of wireless communication modules such as Wi-Fi or Bluetooth, users can control appliances remotely, thereby adding flexibility and convenience [2].

This research aims to design, implement, and test a prototype of such a system using affordable components like Arduino, sensors, and relays, making it accessible for widespread use. By reducing unnecessary energy consumption and increasing user awareness, the proposed system offers a viable solution for modern energy-efficient households. The study also opens pathways for integrating renewable energy sources and advanced machine learning techniques in future developments.

Methodology. The methodology for developing the intelligent mechatronic system involved several key stages: system design, component selection, hardware integration, software development, and testing. The main objective was to build a functional prototype capable of monitoring, analyzing, and controlling household energy consumption in real time, using affordable and widely available electronic components.

The system architecture consists of sensors (current and voltage sensors), a microcontroller unit (Arduino Mega 2560), relay modules for device control, and a Wi-Fi communication module (ESP8266) for remote connectivity. The sensors measure the real-time electrical parameters of individual appliances, including voltage, current, and power usage.

The sensors were connected to the Arduino board, which processes the incoming data. Relay modules were connected to the output pins of the microcontroller, allowing the system to turn appliances on or off based on predefined rules. All components were mounted on a prototyping board to ensure ease of testing and maintenance [3-6].

The software was developed using Arduino IDE and programmed in C/C++. The code includes functions for data acquisition, threshold-based decision-making, device switching, and data logging. A simple mobile application was also developed using Blynk to display power usage and allow users to manually control devices from their smartphones.

A rule-based algorithm was implemented to optimize energy usage. For example, if a device's energy consumption exceeds a threshold during peak hours, the system automatically turns it off or alerts the user. The algorithm can also be modified to include time-based control or integrate pricing models for dynamic energy tariffs.

The prototype was tested in a simulated household environment. Different appliances were connected to the system, and various usage scenarios were created. Data was collected over several days to evaluate the system’s ability to reduce energy consumption. The results showed reliable switching operations, accurate data readings, and a noticeable reduction in power usage during non-essential hours [7].

Results and Discussion. The intelligent mechatronic system developed for optimizing household energy consumption was tested in a controlled environment designed to simulate a typical home setting. The objective was to evaluate the system’s performance in real-time monitoring, decision-making accuracy, energy-saving capability, and user interaction.

The system demonstrated a high level of accuracy in collecting and processing energy usage data. Voltage and current readings were recorded every second, and instantaneous power consumption was calculated and displayed on the mobile application. The sensors used (ACS712 current sensor and ZMPT101B voltage sensor) delivered consistent results with less than ±5% deviation when compared to standard multimeter readings. The data was transmitted via the ESP8266 Wi-Fi module to the Blynk cloud platform, allowing users to view consumption data in real time. This live feedback was crucial in making users more conscious of their energy habits.

One of the key goals of the project was to implement an automated control mechanism. The control algorithm was able to identify excessive energy use and initiate appropriate switching operations through relay modules. For instance, when a specific appliance's power draw exceeded the user-defined threshold (e.g., 200W during peak hours), the system successfully turned off the device. It also sent a notification to the user's smartphone. Manual override options were made available through the app to ensure user control remained intact [8-10].

The relay modules responded with less than 1-second latency, indicating that the system is well-suited for time-sensitive applications. Moreover, the switching accuracy remained consistent throughout testing, with no observed false triggers or delays.

The energy usage data was recorded over a one-week period during both peak and off-peak hours. The test environment included standard appliances such as lighting, fans, a television, and a refrigerator. Without the system in operation, the average daily energy consumption was 7.2 kWh. With the intelligent mechatronic system active, average daily consumption dropped to 5.3 kWh — a reduction of approximately 26%.

Most of the savings were attributed to eliminating standby power consumption (phantom load) and reducing unnecessary appliance use during peak pricing hours. For example, lighting in unoccupied rooms was automatically switched off, and users were prompted to delay use of high-power devices like washing machines to off-peak periods.

The mobile application interface developed via Blynk provided a simple and intuitive user experience. Real-time graphs, energy usage history, and manual control buttons allowed users to stay informed and involved. Feedback collected from test users indicated high satisfaction levels, with users appreciating the remote access and clear display of consumption patterns. However, some users expressed the desire for more advanced features such as usage forecasting or integration with voice assistants like Alexa or Google Assistant.

While the system showed promising results, several limitations were observed:

- The accuracy of energy measurement could vary depending on the type and number of appliances connected.
- The system was dependent on continuous Wi-Fi connectivity for remote access; interruptions caused temporary loss of data transmission.
- The current algorithm was rule-based and did not adapt dynamically to changing consumption habits unless reprogrammed manually.
- To address these limitations, future versions of the system could include:
- Machine learning algorithms for adaptive control.
- Local data storage using SD cards to prevent data loss during connectivity issues.
- Solar panel integration to manage hybrid energy systems.

Compared to commercially available smart plugs or home energy monitors, this system offered a customizable, open-source, and cost-effective alternative. While commercial systems may offer greater polish and integration, they are often expensive and less flexible for research or educational use. The prototype created in this study can be tailored for various household sizes, power ratings, and user preferences.

Conclusion. This research presents the design, development, and testing of an intelligent mechatronic system for optimizing household energy consumption. The system integrates real-time monitoring, automated control of household appliances, and user-friendly interfaces, making it a practical solution for reducing energy waste in residential environments. By combining sensors, microcontrollers, and wireless communication, the system provides valuable insights into energy usage patterns and offers actionable control mechanisms to minimize unnecessary power consumption.

The experimental results demonstrated that the proposed system could achieve an average energy reduction of approximately 26% in a simulated household environment. Most of these savings were attributed to the elimination of standby power losses and the efficient control of energy-intensive devices during peak hours. Additionally, the mobile application provided users with a clear and intuitive interface to monitor energy consumption and manage devices remotely, which significantly improved user engagement and awareness.

While the system performed well in the prototype phase, there are several avenues for further improvement. Future enhancements could include the integration of machine learning algorithms for adaptive control, the incorporation of renewable energy sources such as solar panels, and the development of more advanced prediction models for energy usage based on historical data. Additionally, addressing the system's reliance on Wi-Fi connectivity and improving the accuracy of energy measurement for different appliance types would further enhance its reliability and usability.

In conclusion, the intelligent mechatronic system developed in this study offers a promising solution for optimizing household energy consumption. With its ability to reduce energy waste, provide real-time data, and empower users to make informed decisions, this system holds significant potential for contributing to the global goal of sustainable energy usage. Future work should focus on refining the system, exploring additional features, and expanding its applicability to larger residential and commercial settings.

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