ESP32 Based IoT-Enhanced Automatic Water Heater with Adaptive Temperature Control for Ultimate Comfort and Energy Efficiency

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Abstract

The increasing global demand for hot water systems has led to significant energy consumption, with residential water heating accounting for nearly 18–25% of total household energy usage worldwide, while inefficient heating systems contribute to approximately 30% of avoidable energy loss. Additionally, rapid urbanization and smart home adoption are driving the need for intelligent, connected appliances, with the Internet of Things (IoT)-enabled home automation market projected to surpass 150 billion USD by 2030. Furthermore, varying user schedules and environmental conditions necessitate adaptive systems capable of dynamically adjusting water temperature. Traditional water heaters rely heavily on manual operation, leading to issues such as overheating, energy wastage, delayed heating, and lack of real-time monitoring, which ultimately reduce efficiency and user convenience. They also lack predictive control and fail to adapt to user behavior or environmental variations. To address these challenges, the proposed smart heat geyser utilizes an ESP32 microcontroller integrated with temperature sensors, cloud connectivity, and adaptive control algorithms to enable real-time monitoring and intelligent temperature regulation. The system dynamically adjusts heating based on user preferences, usage patterns, and ambient conditions, thereby minimizing energy consumption and enhancing operational efficiency. Remote access via IoT platforms allows users to control and monitor the system seamlessly, while automated decision-making ensures safety, reliability, and sustainability. This intelligent approach significantly improves performance compared to conventional systems, offering a scalable and energy-efficient solution for modern water heating applications.

Keywords: Adaptive Control, Cloud Connectivity, Energy Efficiency, ESP32, IoT-Based Water Heater, Remote Monitoring, Smart Home Automation, Temperature Sensors

1. Introduction

The global demand for efficient water heating systems has grown substantially due to rising energy consumption and increased urbanization. Recent studies indicate that residential water heating accounts for approximately 18–25% of total household energy usage worldwide, making it one of the major contributors to domestic energy demand [1]. Furthermore, inefficient heating mechanisms are responsible for nearly 30% of avoidable energy losses, highlighting the urgent need for optimized solutions [2]. With the rapid expansion of smart infrastructure, the IoT-enabled home automation market is projected to exceed 150 billion USD by 2030, reflecting a strong shift toward intelligent and connected appliances [3]. In sectors such as smart homes, healthcare facilities, hostels, and industrial environments, the demand for automated [4], energy-efficient, and remotely controllable water heating systems is continuously increasing to meet both comfort and sustainability goals.

Problem Statement: Traditional water heating systems primarily operate on manual control mechanisms, where users switch the system on and off based on their immediate needs. These systems typically lack advanced sensing, communication, and decision-making capabilities, resulting in static operation regardless of environmental or user-specific variations [5]. Conventional geysers often depend on preset thermostats that do not adapt dynamically to changing usage patterns or ambient conditions. As a result, they fail to optimize heating cycles and energy consumption efficiently [6]. Additionally, the absence of connectivity restricts users from monitoring or controlling the system remotely, limiting convenience and flexibility in modern smart living environments.

Research Motivation: In real-time scenarios, these limitations lead to several critical challenges affecting both performance and user experience. Manual operation frequently causes overheating, unnecessary energy consumption, and delayed water availability, particularly when user schedules are unpredictable [7]. The lack of real-time monitoring and adaptive control prevents the system from responding intelligently to varying demand conditions, resulting in inefficiencies and increased operational costs. Safety concerns also arise due to the absence of automated regulation mechanisms, which can lead to excessive temperature levels or system failures. Moreover, traditional systems do not incorporate predictive or learning-based approaches, making them incapable of adapting to user behavior or environmental fluctuations. These challenges emphasize the need for an intelligent, IoT-based solution capable of real-time decision-making, efficient energy utilization, and enhanced user convenience.

2. Literature Survey

Lee et al. [8] proposed a neural network-based energy optimization framework that utilized historical heating patterns and environmental parameters to regulate power consumption in water heating appliances. Gomez et al. [9] proposed a solar-powered smart water heating system that integrated photovoltaic panels with thermal storage units to ensure sustainable and cost-efficient operation. Ahmed et al. [10] proposed a hybrid renewable energy-based water heating solution that combined solar and auxiliary energy sources to achieve continuous heating availability. Mishra et al. [11] proposed an automated energy-switching mechanism that dynamically alternated between solar and electrical heating based on energy availability and temperature thresholds. Chen et al. [12] proposed an Android-based control system that enabled remote monitoring and operation of water heaters through a mobile application interface. The system integrated wireless communication protocols for real-time user interaction and control. Park et al. [13] proposed a smart water heater integration framework that connected heating systems with voice assistants such as Google Assistant and Amazon Alexa for user-friendly operation.

Das et al. [14] proposed a real-time communication model using Message Queuing Telemetry Transport (MQTT) protocol for efficient data transmission between smart water heaters and cloud platforms. Singh et al. [15] proposed an overheat protection algorithm that monitored temperature thresholds and automatically disabled heating elements to prevent system damage. Raj et al. [16] proposed a flow sensor-based dry-run protection mechanism that detected the absence of water flow and deactivated the heating system to prevent damage.

Huang et al. [17] proposed a leakage detection system that utilized Internet of Things (IoT) sensors to identify water leakage and trigger automated alerts and shutdown procedures. Ali et al. [18] proposed a communication architecture that integrated Zigbee and Wi-Fi technologies for reliable data exchange in smart water heating automation systems. The framework ensured efficient device coordination and extended network coverage. Singh et al. [19] proposed an Artificial Intelligence (AI)-driven voice-controlled automation system for smart geysers that enabled intelligent user interaction and automated control. Chowdhury et al. [20] proposed an Internet of Things (IoT)-based smart plug system that enabled real-time energy monitoring and control of water heating devices.

3. Proposed System

The smart heat geyser presented in Figure 1 is designed as an IoT-enabled automatic water heater with adaptive temperature control, ensuring maximum user comfort and energy efficiency. The system consists of multiple components, including a temperature sensor, keypad, auto/manual switch, LCD display, buzzer, IoT connectivity, relay module, and an ESP32 microcontroller, which work together to provide seamless operation.

Modes of Operation: The system offers two distinct modes of operation as shown in Figure 2.

- **Manual Mode**: In this mode, the user has complete control over the geyser's operation. The geyser can be turned ON or OFF at any time based on the user's preference. The current water temperature is displayed on the LCD screen and is also accessible via the IoT web application. The user can monitor temperature levels remotely and manually switch the geyser ON/OFF using the web interface, providing added convenience.
- **Automatic Mode:** In this mode, the system intelligently controls the geyser based on the user's desired temperature settings. The user can set the desired temperature using the keypad or through the IoT web application. The temperature sensor continuously monitors the water temperature and transmits real-time data to the ESP32 microcontroller. When the water reaches the preset temperature, the system automatically turns OFF the geyser to prevent overheating and reduce energy consumption. If the temperature drops below the preset threshold, the system automatically turns the geyser back ON to maintain the desired water temperature. All temperature readings and system statuses are continuously updated on the IoT platform, allowing real-time monitoring from any location.

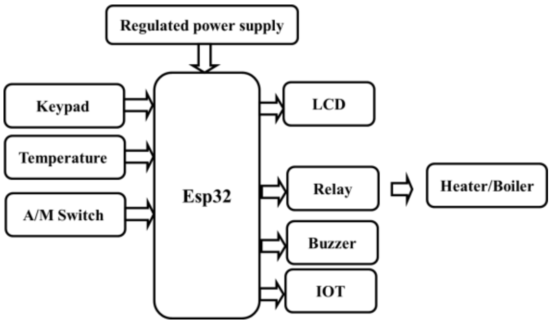

Figure 1. Proposed Block Diagram.

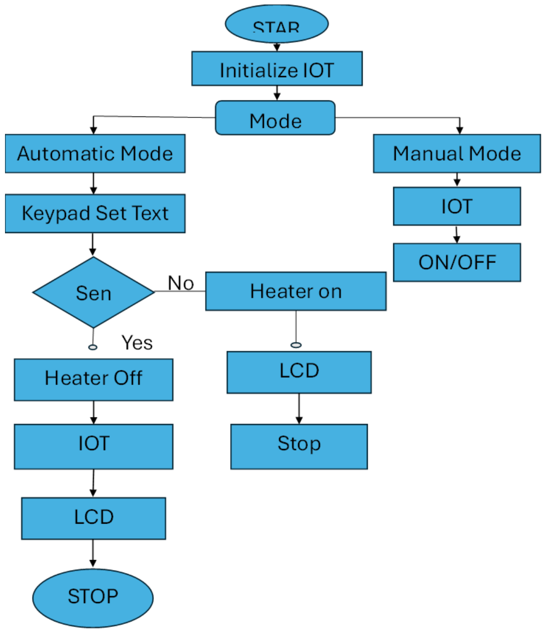

Figure 2. Proposed Flowchart.

The system includes a buzzer that provides alerts in case of abnormal temperature variations or system malfunctions. The system is integrated with a cloud-based IoT platform, allowing users to monitor and control the geyser remotely. The IoT web application displays real-time temperature readings, operational status, and mode settings. Users can adjust settings and receive notifications via the IoT dashboard. A relay module is used to control the ON/OFF switching of the geyser based on the system's mode and temperature conditions.

The hardware components are connected to ESP32 board as shown in Figure 3. The General purpose I/O pins are connected to buzzer, LCD Display, Temperature, relay. 5V RPS is connected to the ESP32. The RPS circuit diagram consists of stepdown transformers, bridge rectifier for AC to DC conversion. voltage regulator 7805 for supplying 5V voltage to the ESP32.

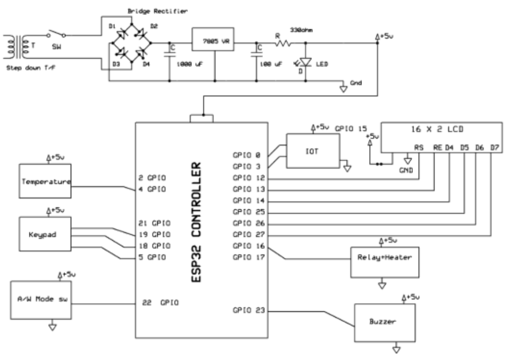

Figure 3. Hardware Oriented Pin Connections to ESP32.

Hardware connected to the ESP32:

- Temperature sensor is connected to GPIO4 pin of ESP32 microcontroller.
- IOT is connected to GPIO0 and 3 pins of ESP32 microcontroller.
- LCD is connected to GPIO12, 13, 14, 25, 26, 27 pins of ESP32 microcontroller.
- Keypad is connected to GPIO5, 18, 19 pins of ESP32 microcontroller.
- Relay with geyser is connected to GPIO16 pin of ESP32 microcontroller.
- Buzzer is connected to GPIO23 pin of ESP32 microcontroller.

4. Results and Discussion

Figure 4 shows the complete hardware setup of the Smart Heat Geyser system. The circuit includes the ESP32 microcontroller, temperature sensor, heating element, relay control circuit, LCD display, and IoT communication module used for monitoring and controlling the geyser.

According to Figure 5, the LCD display shows the geyser operating in manual mode where the user can directly control the heater. The temperature value and system status are displayed on the LCD, indicating that the geyser has been manually turned ON.

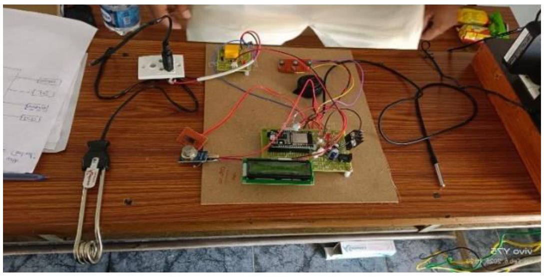

Figure 4. Hardware Circuit of Research Work.

Figure 5. Manual Mode of Operation- Geyser ON

Figure 6. Automatic Mode of Operation- Geyser ON

In automatic mode as shown in Figure 6, the system monitors the temperature and activates the geyser automatically when the temperature falls below the set threshold. The LCD screen displays the current temperature, set temperature, and the geyser status as ON. According to Figure 7, when the water temperature reaches the predefined limit, the system automatically turns the geyser OFF to prevent overheating and reduce energy consumption. The LCD screen displays the updated temperature and system status.

The IoT web interface as shown in Figure 8 displays the operational parameters of the geyser system such as temperature, set temperature, operating mode, and geyser status. This enables users to remotely monitor the water heater through the internet.

Figure 7. Geyser OFF in Auto Mode

Figure 8. Output in Web Page

5. Conclusion

The Smart Heat Geyser represents a transformative step in water heating technology by integrating IoT capabilities, adaptive temperature control, and cloud connectivity. With ESP32, advanced sensor integration, and real-time monitoring, the system ensures optimal user comfort while significantly improving energy efficiency. The implementation of intelligent algorithms allows for dynamic temperature adjustments based on user preferences and environmental conditions, effectively reducing energy waste and supporting sustainable practices. By offering remote accessibility, automated regulation, and data-driven optimization, the Smart Heat Geyser stands as a superior alternative to traditional water heating solutions. This innovation not only enhances convenience but also contributes to cost savings and environmental sustainability, making it a practical and future-ready solution for modern households and industries.

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