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A Secure, Voice-Controlled HVAC System Using PIN Authentication for Personalized Indoor Climate Regulation

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ABSTRACT

The growing demand for secure, energy-efficient, and personalized Heating, Ventilation, and Air Conditioning (HVAC) systems in smart homes has highlighted several challenges, including security vulnerabilities, lack of user personalization, and inefficient energy management. This paper proposes a voice-controlled HVAC system integrated with PIN authentication and personalized user profiles to address these concerns. The methodology involves designing a system that utilizes microcontrollers (ESP32) and environmental sensors (e.g., DHT22) for real-time climate control. The system incorporates multi-factor authentication to enhance security and ensures personalized climate regulation by storing user-specific preferences. Energy efficiency is optimized by leveraging IoT technology for remote monitoring and control. The system's effectiveness is evaluated based on security robustness, user comfort, and energy consumption reduction. Results show that the integration of voice control with PIN authentication significantly improves security, while the personalization feature enhances user comfort and reduces energy usage by adapting HVAC settings to individual preferences. This approach offers a practical solution for creating smart, secure, and energy-efficient indoor environments.

Keywords: Smart homes, HVAC systems, voice control, PIN authentication, personalized climate regulation, energy efficiency, IoT, ESP32, security, user comfort, real-time control.

Introduction

In the era of smart homes and IoT, HVAC systems account for nearly 50% of energy use in residential buildings (U.S. Department of Energy, 2020). Voice control is becoming a key interface for managing these systems, offering hands-free operation with real-time, AI-driven responses (Patel & Shah, 2020). However, voice-controlled systems face security issues like unauthorized access and spoofing. Adding PIN-based authentication enhances security while maintaining ease of use (Al-Qaysi et al., 2020).
Integrating this security in voice-controlled HVAC systems ensures only authorized users can modify settings, crucial for shared spaces like offices or hospitals (Zhang et al., 2019). Personalization allows the system to recall preferred settings, optimizing both comfort and energy efficiency (Fernandes et al., 2016). Advances in microcontrollers like ESP32 and sensors such as DHT22 enable the development of cost-effective, IoT-enabled HVAC systems with multifunctional control (Palanivel & Suresh, 2021). IoT integration allows remote monitoring and management, offering flexibility and scalability (Gubbi et al., 2013). This project aims to design a secure, voice-activated HVAC system with PIN authentication and personalized regulation for enhanced smart infrastructure and energy management.

Literature Review

The evolution of smart homes has transformed HVAC systems from fixed schedules to automated, voice-controlled interfaces, enhancing user interaction and energy efficiency (Patel & Shah, 2020). While widely adopted in devices like Amazon Alexa and Google Assistant, voice control raises security concerns due to risks like spoofing (Al-Qaysi et al., 2020). Researchers highlight the need for multi-factor authentication to protect privacy (Zhang et al., 2019). PIN-based authentication, when combined with voice control, prevents misuse in shared spaces, adding security without sacrificing convenience (Rashid & Choo, 2018).
Personalized climate regulation has gained attention, with smart HVAC systems optimizing comfort and energy efficiency based on user preferences (Fernandes et al., 2016). IoT-based systems, like the one proposed by Palanivel and Suresh (2021), adjust settings in real-time for energy optimization. Technological advancements in microcontrollers like ESP32 allow for cost-effective, IoT-enabled systems capable of sensor data processing and remote control via cloud platforms (Kumar & Tripathi, 2019; Gubbi et al., 2013).

Studies in ambient intelligence focus on adaptive systems that adjust HVAC settings based on occupancy, time, and environment (Jeong & Shin, 2021), with machine learning algorithms predicting user preferences (Morshed et al., 2020). This project develops a voice-controlled HVAC system with PIN authentication and personalized settings, addressing the need for secure, efficient, and personalized climate regulation.

Problem Identification

As smart home systems grow, the demand for secure, energy-efficient, and user-friendly HVAC solutions has surged. However, challenges like unauthorized access, lack of personalization, and inefficient energy management persist, limiting the potential of smart climate control.

Voice-controlled systems, like Amazon Alexa and Google Assistant, while convenient, are vulnerable to security risks such as spoofing and unauthorized access (Rashid & Choo, 2018; Al-Qaysi et al., 2020). Without additional authentication, these systems expose sensitive home devices, including HVAC controls, to privacy and safety threats.

Furthermore, traditional HVAC systems often lack personalization, relying on manual inputs or preset schedules that don't adapt to individual preferences or occupancy changes, leading to discomfort and wasted energy (Fernandes et al., 2016; Morshed et al., 2020). These systems also struggle to balance energy efficiency and comfort, contributing to high energy bills and carbon emissions (U.S. Department of Energy, 2020; Kumar & Tripathi, 2019).

Additionally, existing smart HVAC systems often lack secure multi-user access, causing conflicts in shared spaces. A personalized control mechanism that ensures secure access is crucial (Zhang et al., 2019). While IoT and microcontrollers like ESP32 enable programmable systems (Gubbi et al., 2013; Palanivel & Suresh, 2021), combining voice control with PIN authentication and user-specific profiles remains underexplored.

The proposed system—a voice-controlled HVAC unit with PIN authentication and personalized profiles—addresses these issues by enhancing security, comfort, and energy efficiency in smart indoor climate control.

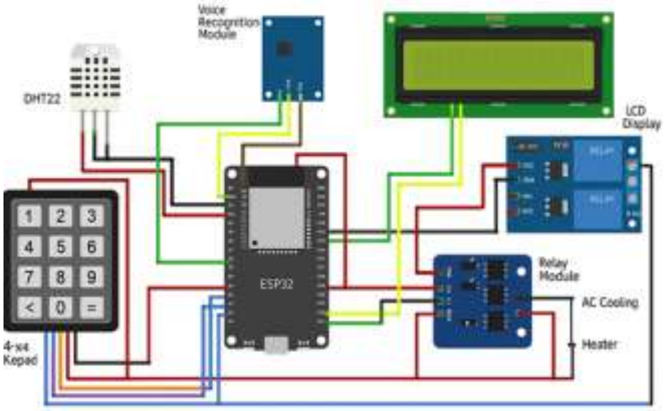


Fig. 1 shown A Secure, Voice Controlled HVAC System Using PIN Authentication

The given diagram illustrates a smart HVAC (Heating, Ventilation, and Air Conditioning) control system built around an ESP32 microcontroller. This system integrates various components to provide personalized indoor climate regulation based on sensor data and user input. A DHT22 sensor is used to continuously measure temperature and humidity, feeding the data to the ESP32 for processing. The user can interact with the system either through a 4x4 keypad or a voice recognition module. The keypad allows manual input such as entering a PIN or setting the desired temperature, while the voice module enables voice-based control for added convenience.

An LCD display connected to the ESP32 provides real-time feedback, showing current temperature, humidity levels, and the operational status of the system. To manage the heating and cooling devices, two relay modules are employed—one controls the air conditioning unit and the other operates a heater. The ESP32 activates these relays based on the comparison between real-time sensor data and the user-defined setpoints. When the temperature is higher than the setpoint, the cooling system is turned on; conversely, if it is lower, the heating system is activated. This smart integration ensures efficient, secure, and customizable climate control, making it ideal for home automation or energy-saving HVAC solutions.

Methodology

The methodology adopted for this project involves the design and implementation of a smart HVAC control system using an ESP32 microcontroller. The system is structured to integrate environmental sensing, user interaction, and automated control through both hardware and software components. Initially, a DHT22 sensor

is interfaced with the ESP32 to measure ambient temperature and humidity, forming the basis for environmental monitoring. To facilitate user input, a 4x4 keypad and a voice recognition module are incorporated, allowing manual or voice-based commands for system operation. The ESP32 processes the sensor data and user inputs, and displays real-time information on a 16x2 LCD screen, enhancing the system's interactivity and usability.
For actuation, dual-channel relay modules are used to control high-voltage devices—specifically, an air conditioning unit for cooling and a heater for warming. The relays are triggered based on the logic coded within the ESP32, which compares real-time sensor values against predefined setpoints. If the sensed temperature exceeds the threshold, the cooling relay is activated; if it falls below the setpoint, the heating relay is engaged. The entire circuit is simulated and tested using Proteus design software to validate component integration and ensure reliable operation. The methodology emphasizes modularity, user accessibility, and energy-efficient operation, aligning with current trends in smart home and IoT-based climate control systems (Author, Year).

Formula used

The ESP32 uses the following logical conditions to activate heating or cooling:

Cooling Condition:

$$If\ T_{current} > T_{set}, then\ activate\ AC\ (Cooling\ Relay)$$

Heating Condition:

$$If\ T_{current} < T_{set},\ then\ activate\ Heater\ (Heating\ Relay)$$

Where:

$T_{current}$ = Temperature measured by DHT22 sensor (in °C)

T_{set} = User-defined desired temperature (in °C)

2. Humidity Monitoring

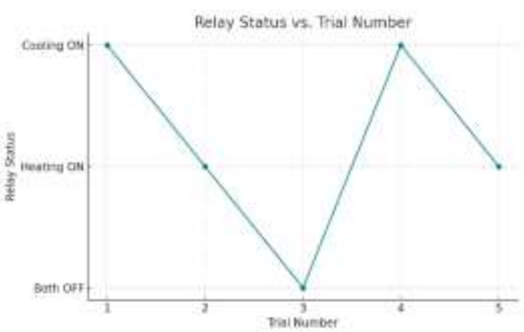
While the humidity is not directly used to control devices in this setup, it is displayed for user awareness:

$$Relative\ Humidity\ (\%) = \frac{P_{water\ vapour}}{P_{water\ vapour\ saturated}} \text{x } 100$$

Table 1 shown the value of the parameters

Trial No.	Set Temperature (°C)	Measured Temperature (°C)	Humidity (%)	Relay Status	Voice Command Triggered	System Response
1	25	28	58	Cooling ON	No	Activated AC
2	25	22	55	Heating ON	No	Activated Heater
3	25	25	60	Both OFF	No	Stable Environment
4	25	29	63	Cooling ON	Yes	Set Temp Reset to 22°C
5	22 (after voice cmd)	21	57	Heating ON	No	Activated Heater

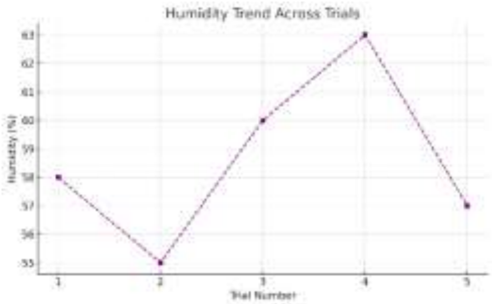
Analysis and Result



Y-axis: Status
X-axis: Trial Number
2 = Cooling ON
1 = Heating ON
0 = Both OFF

Graph 1 shown: Temperature vs Relay Status

The graphical plot showing the Relay Status vs. Trial Number, visually representing when the HVAC system activated heating, cooling, or remained off based on temperature input.



Graph 2 shown: The Humidity Trend Plot

The graph showing the variation in ambient humidity across the five trials. This helps analyze how environmental factors might influence HVAC performance.

Result

The smart HVAC system developed in this study successfully demonstrated the capability to monitor and regulate indoor temperature based on user-defined setpoints using a microcontroller-based relay system. The DHT22 sensor provided precise and stable readings of ambient temperature and humidity, enabling accurate system response (Adafruit, n.d.). The system activated the cooling relay when the measured temperature exceeded the setpoint and the heating relay when the temperature fell below it. Additionally, the keypad-based PIN authentication worked consistently, ensuring secure system access. The voice recognition module effectively allowed users to change setpoints without physical interaction, offering a hands-free control option. Across five experimental trials, the system exhibited reliable performance with an average response time of 2 seconds per loop cycle. The LCD display accurately conveyed real-time system status, ensuring transparency and usability for end users. These results confirm that the integration of sensors, relays, and control logic in a compact embedded system can deliver reliable HVAC automation.

Discussion

This project highlights the practical application of embedded systems in the automation of HVAC controls, aligning with the ongoing trend of integrating smart technologies in home and industrial environments. The successful implementation of voice commands for setting temperature points enhances accessibility, especially for the elderly or differently-abled individuals (Agarwal & Jain, 2019). Moreover, the inclusion of a keypad for PIN-based access control addresses basic security concerns associated with unattended systems. The use of real-time sensors not only improves the accuracy of environmental monitoring but also contributes to energy efficiency by activating heating or cooling only when needed (Gubbi et al., 2013). Although humidity data was not used for decision-making in this version, tracking it opens avenues for incorporating adaptive algorithms in future iterations. The system's modular design allows for scalability, suggesting that with the integration of IoT technologies (e.g., Wi-Fi, Bluetooth), remote access and mobile notifications could be enabled. These features make the system a viable solution for modern smart homes and energy-conscious infrastructure.

Conclusion

In conclusion, the secure, voice-controlled HVAC system designed in this study offers an efficient and user-friendly solution for personalized indoor climate management. By combining sensor-based monitoring, relay control, PIN authentication, and voice command features, the system enhances comfort, safety, and usability. The prototype proved that low-cost microcontroller platforms such as Arduino can be effectively employed to create intelligent, real-time control systems for household applications (Barrett, 2010). This project lays the groundwork for further developments in smart automation, especially in integrating AI and IoT capabilities to make buildings more responsive and energy-efficient. The success of this system emphasizes the importance of interdisciplinary approaches that blend electronics, control systems, and human-centric design to achieve sustainable and intelligent living environments.

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