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MODULAR APPROACH TO BUILDING A HARDWARE-SOFTWARE PLATFORM FOR SMART HOME AUTOMATION: FROM SIMPLE RULES TO INTELLIGENT SCENARIOS

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ABSTRACT

Background. This article addresses the challenge of creating flexible, scalable, and user-adaptive automation systems that can evolve in response to changing needs and technological advancements. The research focuses on developing an IoT-oriented smart home automation system designed for intelligent self-adjustment based on environmental conditions and remote device control. A key objective is to substantiate the benefits of a modular architectural approach for extending system functionality and effectively utilizing complex adaptive algorithms to enhance performance.

Materials and Methods. To achieve the set goals, a novel hardware-software platform architecture is proposed, based on the division of functionality into independent modules. The use of the Home Assistant platform, its integrations, HACS, and Lovelace cards for intuitive system implementation and user interaction was investigated. The methodology includes practical examples of creating automation scenarios, including intellectualization through machine learning methods.

Results and Discussion. Comprehensive analysis demonstrated the high effectiveness and practical viability of the proposed modular approach. The developed solutions provide flexibility in system settings, ensuring ease of implementation even for complex configurations, and scalability, allowing for seamless integration of new devices and expanded coverage areas. The obtained data illustrate the possibilities of developing both simple and complex scenarios with elements of artificial intelligence and learning, including adaptive lighting, climate control, and security protocols.

Conclusion. The presented modular approach enables the application of broad customization and scalability capabilities for a smart home platform. The integration of open-source software tools, a wide range of sensors, and diverse communication interfaces enables the creation of systems ranging from basic automations to complex intelligent scenarios. This intelligent integration of scenario logic expands overall automation capabilities, transforming conventional systems into convenient and adaptive living environments.

Keywords: Home Assistant, hardware and software platform, automation

INTRODUCTION

In the context of the development of Internet of Things (IoT) and cyber-physical systems technologies, there is a growing demand for effective automation solutions for residential and commercial premises. "Smart home" systems enable increased comfort, security, and energy efficiency through the integration of hardware controls with intelligent software. The modular approach is particularly relevant, providing flexibility, scalability, and adaptation to individual user needs.

Modern solutions for smart home automation systems are implemented based on wired and wireless infrastructures. Wireless solutions (Wi-Fi, Zigbee, Bluetooth) are characterized by ease of installation, flexibility, and scalability, but have drawbacks such as latency, dependence on a stable connection, and a limited range [1]. Wired systems (Ethernet, RS-485, KNX) provide high stability, security, and durability, but require more complex installation and planning. The choice between these options depends on the user's needs and installation conditions [2-4].

One significant obstacle to the development of integrated smart home automation systems is the heterogeneity of communication protocols, which hinders the seamless interaction of diverse devices. A significant number of devices operate within specialized ecosystems or use specific data transmission technologies, creating fragmentation and complicating their coordinated operation. To mitigate this problem, developments are underway for unified standards, in particular the Matter protocol, whose task is to provide a homogeneous communication environment for various devices and ecosystems. New standards, such as Matter, simplify integration between manufacturers, including Google, Amazon, and Samsung. Matter is particularly effective in combination with Thread — an energy-efficient network protocol for low-power devices. Thread provides a robust mesh topology for devices, while Matter provides a unified command and data protocol [5].

There are a number of popular automation platforms on the market: Home Assistant, Domoticz, OpenHAB, and Homebridge. Home Assistant is becoming a leader due to its flexible structure, hundreds of integrations, and community support. It is used for simple integration, automation, and visualization [3,4]. There are also commercial solutions from Google, Amazon, and Apple that provide cloud services but have limited customization and dependence on the Internet. In contrast, local systems like Home Assistant allow for fully autonomous operation with a high level of privacy [6].

The development of wireless technologies has led to the emergence of new protocols (Thread, LoRa, NB-IoT) that focus on low power consumption and long transmission distances [7]. Compatibility and security remain a problem: many devices have their own protocols without open documentation. Therefore, open platforms with HACS, MQTT, and REST API support are becoming increasingly important [8].

Automation systems are also being integrated with artificial intelligence platforms such as Google TensorFlow and OpenAI API, which allows for the implementation of adaptive scenarios based on user data and event history [9]. In addition, the role of educational solutions is growing — automation systems are used in laboratories, engineering courses, and scientific research [10].

The objective of this study is to provide a rationale for and illustration of the benefits inherent in a modular approach to constructing smart home automation platforms. This encompasses demonstrating how modularity facilitates the expansion of functional capabilities.

MATERIALS AND METHODS

The paper presents a hardware-software implementation of a central hub for a smart home based on a mini-PC with the possibility of installing Home Assistant. The system supports a wide range of sensors and actuators, allowing for the implementation of both simple automations and complex scenarios. The open platform Home Assistant can be installed on Raspberry Pi, Orange Pi, Intel NUC, NAS, or ARM platforms. This versatile platform is designed for local control and automation of Internet of Things (IoT) devices from various manufacturers. It operates autonomously, without the need for connection to cloud services or constant internet access and provides support for a wide range of communication protocols. Home Assistant allows for the continuous development of automation solutions for residential/industrial use by adding additional programs for new objects, created by open-source community members or by creating custom code using programming languages supported by the platform (Python, YAML, JSON, JavaScript, visual programming-based development tools, etc.) [11].

Depending on the user's level and system flexibility requirements, four main installation options are provided: Home Assistant OS, Container, Supervised, and Core. The system allows for the integration of various devices and services into a unified automation infrastructure, using a modular approach, functional blocks, and logical control algorithms.

Modularity is one of the key principles for building a flexible and scalable smart home system. It allows for the separation of system functionality into independent components that are easily updated, replaced, or expanded.

A block diagram of the system's hardware part is shown in **Fig. 1**.

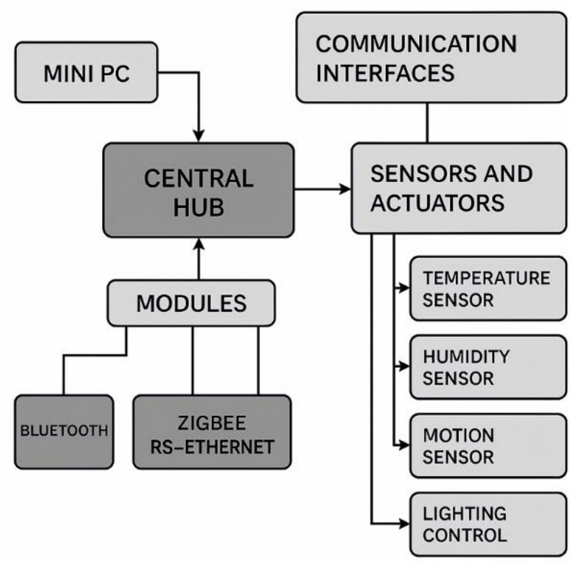


Fig. 1. Block diagram of the hardware part of the smart home automation system.

The physical structure of the system includes:

- A central hub operating on a single-board computer;
- Sensors: temperature, humidity, light, motion, smoke, water leak;
- Actuators: relays, lighting controllers, servomotors, infrared transmitters;
- Communication interfaces: wired (Ethernet, RS-485, UART) and wireless (Wi-Fi, Zigbee, Z-Wave, Bluetooth, Thread/Matter);
- Auxiliary modules: power supplies, neural accelerators, IR modules, audio interfaces, and displays.

At the software level, modularity is realized through integrations - ready-made software modules for connecting devices and services. A diagram of the software architecture of a smart home system using Home Assistant as the main open source control platform is shown on **Fig. 2**.

For displaying the status of smart devices and providing their control in Home Assistant, there is a flexible and fully customizable user interface called Lovelace. Thanks to its modular structure, users can compose information panels from various cards,

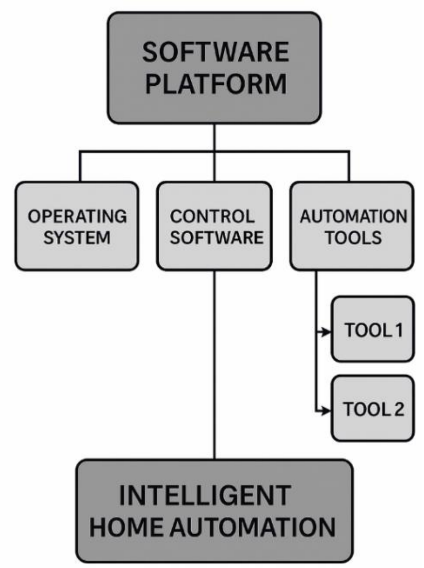


Fig. 2. Block diagram of the software architecture of a smart home system.

displaying only the necessary data and control elements (**Fig. 3a**). A special feature of Lovelace is its extensive customization options, which include the use of third-party extensions such as the Custom Button Card (**Fig. 3b**) for creating unique buttons withdifferent functions and styles, the application of circular indicators for visual representation of levels or values, as well as deep CSS styling for complete control over the interface's appearance [11]. This allows for the adaptation of the interface to individual needs and the creation of intuitive and aesthetically pleasing smart home control panels.

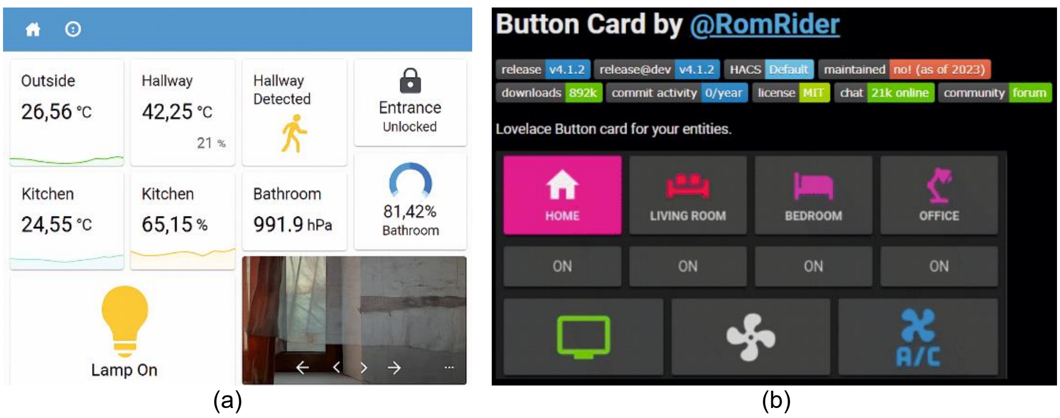
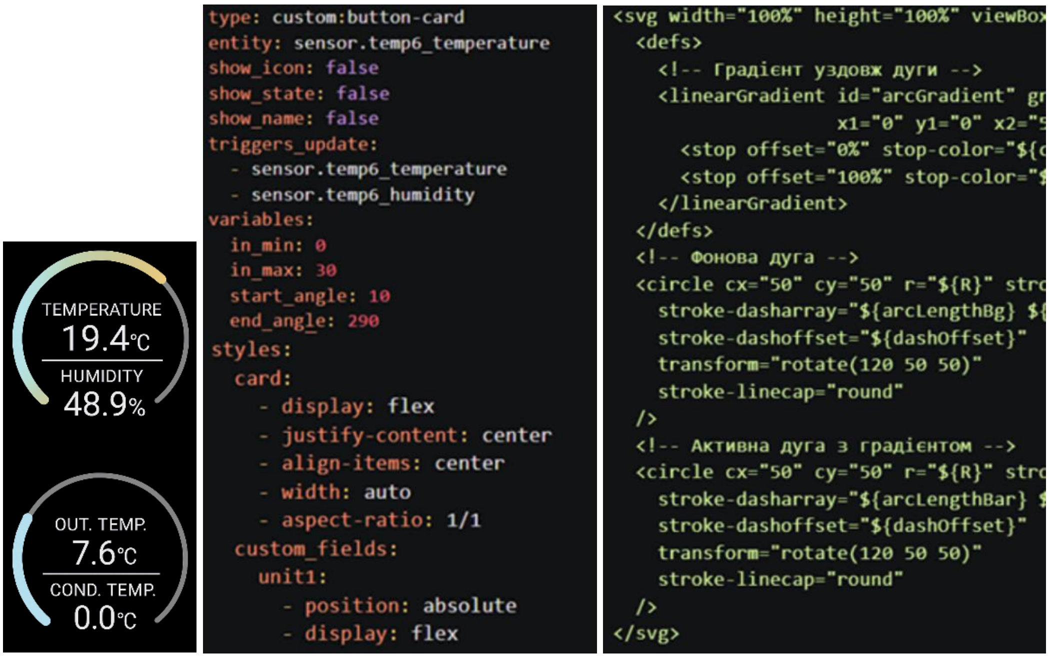


Fig. 3. Visualization of the status of devices (a) and controls (b) in the Lovelace interface.

A key role in expanding the functionality of the Home Assistant platform is played by the Home Assistant Community Store (HACS), acting as an unofficial but extremely popular marketplace for community-contributed add-ons. This tool significantly simplifies the process of integrating custom extensions that are not included in the standard distribution, providing access to a wide range of content. Among the available add-ons are custom integrations that provide support for a greater number of devices and services, interface elements for Lovelace that allow for the creation of unique visualizations and controls, ready-made automation blueprints that users can easily adapt, as well as themes for personalizing the look and feel of the interface.

Fig. 4 demonstrates the application of the Custom Button Card in the Lovelace UI of the Home Assistant platform for creating customized control and data visualization elements. Two cards are presented (**Fig. 4a**), displaying current and external temperature and humidity readings. **Fig. 4b** shows a fragment of the YAML configuration for creating such a custom card. Among the parameters, you can see the definition of the card type (type: custom:button-card), the binding to a specific entity (entity: sensor.temp6_temperature), the configuration of icon and state display (show_icon: false, show_state: false), as well as the definition of variables for minimum and maximum values, and start and end angles for the circular indicator. including binding to the entity and defining display parameters.



(a) (b) (c)

Fig. 4. Implementation of data visualization using Custom Button Card (a), YAML configuration (b), and SVG graphics (c).

The presented SVG code fragment (**Fig. 4c**) implements the visualization of a circular indicator using gradients and dynamic filling via the stroke-dasharray and transform: rotate() attributes. Thus, by integrating YAML configurations and SVG graphics into the Custom Button Card, it is possible to create complex and visually informative interface elements for controlling and monitoring smart home parameters in Home Assistant.

RESULTS AND DISCUSSION

An important element for building complex and adaptive automation systems in Home Assistant is Helpers. These are built-in tools that allow users to create their own logical entities to extend the capabilities of automations, scripts, and the Lovelace interface. These entities can take various forms, including logical variables (boolean values), numeric inputs, selectors, text fields, timers for counting down time, and counters for recording events. Helpers act as abstractions that store a certain state or value, which can be used as a condition for triggering automations, as a variable in scripts, or as a data source for display in the user interface. Thanks to their flexibility, Helpers allow for the implementation of more complex logic and the creation of more interactive and personalized smart home automation scenarios. For example, using a numeric helper, you can set a target temperature for a thermostat, and a boolean helper can display the "home" or "away" state, influencing the behavior of other devices. Timers and counters, in turn, open up possibilities for creating automations that depend on time or the number of certain events [4].

Automation scenarios in smart home systems have evolved from simple conditional rules to complex intelligent algorithms. The simplest scenarios are implemented based on "if → then" logic. They contain triggers (events), conditions, and actions. For example, if the motion sensor is activated after 10:00 PM → turn on the night light with 20% brightness. Scenarios can include multiple conditions, delays, and repetitions. For example, if there is motion in the room and the illuminance is < 50 lx → turn on the light. **Fig. 5** shows an example of implementing a lighting control scenario based on the time of day. During the day, from 7:00 AM to 11:00 PM, the system automatically sets full brightness and a cool color temperature of the light, providing optimal lighting for active tasks. At night, from 11:00 PM to 7:00 AM, the lighting switches to a low brightness mode with a warm color temperature, creating a cozy atmosphere for relaxation. This approach not only automates routine operations but also adapts the environment to the needs of users, contributing to their comfort and well-being.

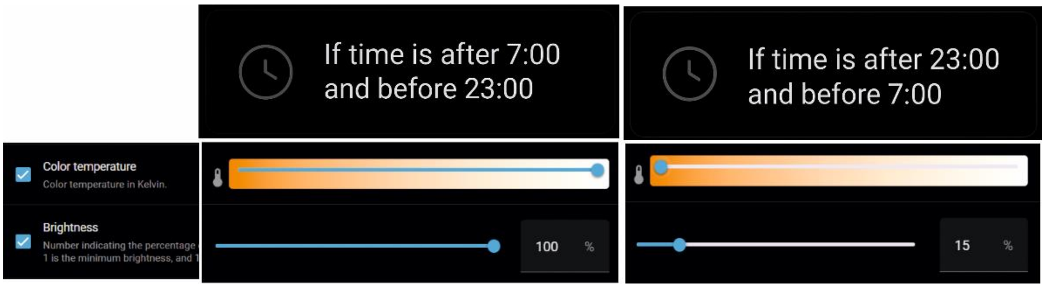


Fig. 5. Algorithm for automatic switching of lighting modes depending on the time of day.

The proposed solution also enables the implementation of scenarios such as "night mode," "vacation," and "energy saving," based on the analysis of input data and logic, and includes a web interface for visual control and event history.

Intelligentization of scenarios in smart home systems involves the transition from simple automation rules to complex, adaptive algorithms capable of responding to changing conditions and user needs. This is achieved through the integration of machine learning and artificial intelligence methods, allowing the system to analyze data from sensors, user interaction history, and external factors. Based on this analysis, the system can automatically adjust environmental parameters, optimize energy consumption, enhance security, and provide personalized comfort. Thanks to the support of Python scripts, Node-RED, and REST API, users can create complex scenarios such as adapting lighting to sleep patterns, anomaly detection, and prediction based on past behavior. The use of local machine learning models (TensorFlow Lite, Edge AI) allows for processing without transferring data to the cloud.

Thus, Home Assistant facilitates the transition from elementary reactions to events to complex, adaptive behavior of the smart home system, taking into account context, environmental conditions, and user needs.

With the rise of computational capabilities and the widespread adoption of machine learning (ML) and artificial intelligence (AI) technologies, automated systems have reached a new level of adaptability. AI enables smart home platforms to expand their functionality by predicting user behavior, recognizing patterns in sensor data, adapting to daily routines, and autonomously adjusting system operation modes.

For instance, using classification or time series prediction algorithms, a smart home system can anticipate when a user is likely to return home and activate lighting, climate control, or security features in advance. AI integration also unlocks anomaly detection capabilities, allowing the system to identify irregularities such as water leaks, unusual activity patterns, or excessive energy consumption and respond accordingly. Moreover, natural language processing tools provide voice command recognition and interpretation of textual queries for generating new automation scenarios. Within the Home Assistant platform, integration with Python-based tools (e.g., TensorFlow, scikit-learn) enables the development of custom analytics and control modules. These tools empower both developers and advanced users to design a truly intelligent and context-aware home environment, facilitating personalized comfort, safety, and energy efficiency.

Fig. 6 illustrates how an adaptive climate control system utilizes AI algorithms to process environmental and behavioral data. The system analyzes both sensor inputs and external conditions to make real-time decisions, adjusting heating, ventilation, and cooling systems accordingly. This structure enables continuous improvement of system performance and user satisfaction through localized learning and personalized control logic.

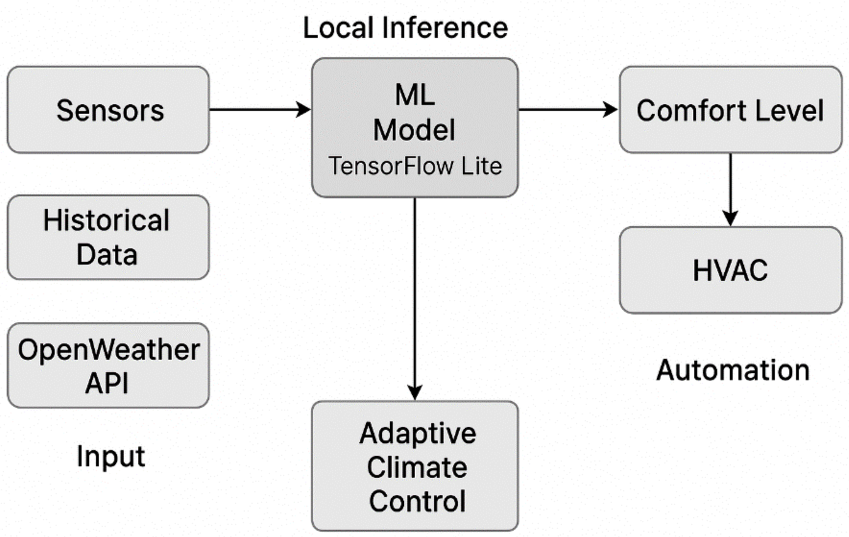


Fig. 6. Block diagram of an AI-driven adaptive climate control scenario

CONCLUSION

The paper investigates a modular approach to building a hardware and software platform for smart home automation. The analysis has shown that modularity is a key factor in creating flexible, scalable, and adaptable systems tailored to the needs of users. The proposed architecture, based on the separation of functionality into independent hardware and software components, differs from traditional monolithic systems and significantly simplifies the process of system expansion, integration of new devices, and services. The considered examples of using the Home Assistant platform, its integrations, HACS, and Lovelace cards — particularly the developed custom cards for data visualization — demonstrate the extensive customization capabilities and the potential for creating both simple and complex automation scenarios. Furthermore, the implementation of adaptive, AI-driven scenarios highlights the transition from static rules to intelligent behavior. Integrating machine learning models within the modular framework enables real-time decision-making, anomaly detection, and personalized environmental control. This elevates the functionality of smart home systems to a new level of context awareness and user-centered intelligence. The proposed principles and solutions can be applied to a variety of applications, from basic lighting control systems to comprehensive environments that provide enhanced safety, comfort, and energy efficiency. Further research will focus on the development of self-scaling algorithms, optimization of energy consumption across modules, and the enhancement of cybersecurity in intelligent automation platforms.

COMPLIANCE WITH ETHICAL STANDARDS

The authors declare that they have no competing interests.

AUTHOR CONTRIBUTIONS

Conceptualization, [V.S., O.S.]; methodology, [M.S.]; validation, [O.S.]; investigation, [V.S.]; writing – original draft preparation, [O.S.]; writing – review and editing, [M.S.]; visualization, [V.S.].

All authors have read and agreed to the published version of the manuscript.

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МОДУЛЬНИЙ ПІДХІД ДО ПОБУДОВИ АПАРАТНО-ПРОГРАМНОЇ ПЛАТФОРМИ АВТОМАТИЗАЦІЇ РОЗУМНОГО БУДИНКУ: ВІД ПРОСТИХ ПРАВИЛ ДО ІНТЕЛЕКТУАЛЬНИХ СЦЕНАРІЇВ

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АНОТАЦІЯ

Вступ. Стаття присвячена проблемі створення гнучких, масштабованих та адаптованих до користувача систем автоматизації, які можуть розвиватися зі змінними потребами та технологічними досягненнями. Дослідження зосереджено на розробці IoT-орієнтованої системи домашньої автоматизації, здатної інтелектуально налаштовуватися на основі умов середовища та дистанційно керувати пристроями. Ключовою метою є обґрунтування переваг модульного архітектурного підходу для розширення функціональності та використання адаптивних алгоритмів.

Матеріали та методи. Для досягнення поставлених цілей запропоновано архітектуру апаратно-програмної платформи, що базується на розділенні функціональності на незалежні модулі. Досліджено використання платформи Home Assistant, її інтеграцій, HACS та карток Lovelace для інтуїтивної реалізації системи та взаємодії з користувачем. Методологія включає практичні приклади створення сценаріїв автоматизації, включаючи інтелектуалізацію за допомогою методів машинного навчання.

Результати та обговорення. Комплексний аналіз продемонстрував високу ефективність та практичну життєздатність запропонованого модульного підходу. Розроблені рішення забезпечують гнучкість налаштувань, гарантуючи легкість впровадження навіть для складних конфігурацій, масштабованість, дозволяючи інтегрувати нові пристрої та розширювати зони покриття. Отримані дані ілюструють можливості розробки як простих так і комплексних сценаріїв з елементами штучного інтелекту та навчання, включаючи адаптивне освітлення, клімат-контроль та протоколи безпеки.

Висновки. Представлений модульний підхід дозволяє застосовувати широкі можливості налаштування та масштабованості для платформи розумного будинку. Інтеграція програмних засобів з відкритим вихідним кодом, широкого спектру сенсорів та різноманітних інтерфейсів зв'язку дозволяє створювати системи, починаючи від базових автоматизацій до складних сценаріїв з елементами інтелекту. Інтелектуальна інтеграція сценарної логіки розширює загальні можливості автоматизації, перетворюючи звичайні системи на зручні та адаптивні житлові середовища.

Ключові слова: Home Assistant, апаратно-програмна платформа, сценарії автоматизації

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