ІНФОКОМУНІКАЦІЙНІ ТЕХНОЛОГІЇ ТА ЕЛЕКТРОННА ІНЖЕНЕРІЯ
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DESIGNING AN INTEGRATED MONITORING SYSTEM WITH ADAPTIVE MODULAR ARCHITECTURE AND ESP-NOW WIRELESS INTERACTION

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The article presents the development of an integrated system for monitoring and managing residential environment parameters, based on the ESP32 microcontroller and the ESP-NOW wireless communication protocol. The proposed system features an adaptive architecture with a clearly defined modular structure, ensuring flexibility, scalability, and ease of operation. The choice of the ESP32 microcontroller as the central element of the system is justified by its high performance, energy efficiency, the availability of a wide range of peripheral interfaces, and support for Wi-Fi, Bluetooth, and ESP-NOW wireless connectivity. This technology is key to the modular architecture, providing high-speed, stable, and energy-efficient data exchange between components, which eliminates the need for an external router or cloud services. The functional features and interaction of each of the four main modules are described: the central controller, which performs comprehensive data processing and provides the user interface; the climate control module, responsible for accurate monitoring of temperature and relative humidity; the motion and lighting control module, which detects presence and regulates light intensity; and the peripheral device control module, designed for automating external equipment. Particular attention is paid to the implementation of fast and energy-efficient wireless data transmission, as well as the construction of an intuitive user interface on a touch-sensitive TFT display. This interface allows for system control in both fully automatic and manual modes, providing the user with complete control and customization capabilities. The results of a comprehensive experimental study conducted on a real system prototype convincingly demonstrate its high effectiveness in monitoring climate parameters, automatic lighting regulation, and reliable control of external devices. Integrated smart systems of this type significantly contribute to enhancing residents' comfort, optimizing energy resource consumption, and ensuring rational space utilization through individual adaptation of functionality to user needs.

Keywords: *modular system, home monitoring, ESP32 microcontroller, ESP-NOW, energy efficiency.*
UDC: 621.382

Introduction

Integrated Monitoring Systems (IMS) are fundamentally unified structures designed for collecting, analyzing, and processing data from various monitoring points. These systems operate in real-time, combining different data streams for holistic, informed decision-making [1]. Such systems find wide application both in industry, for controlling production processes, monitoring equipment, and ensuring occupational safety, and in residential buildings, where they form the basis for “smart” homes, providing comfort, security, and energy efficiency through the automation of climate control, lighting, and security systems. The integration of microcontrollers and IoT technologies allows for effective energy management, optimized space utilization, and significantly improved security.

Today, the market offers a multitude of home automation solutions, but most of them encounter certain limitations. These include high cost, complex setup, and insufficient flexibility for adaptation to individual user needs. These factors often become an obstacle to the widespread implementation of “smart” technologies in everyday life. Meanwhile, the growing popularity of microcontrollers opens up new opportunities for creating individual projects in the field of the Internet of Things (IoT) [2, 3]. The ESP32 microcontroller deserves special attention, as it successfully combines high performance, energy efficiency, and an affordable price. This makes it an ideal choice for developing flexible and scalable home monitoring and automation systems that can overcome the existing shortcomings of commercial offerings.

2. Analysis and problem formulation

Existing approaches to smart systems demonstrate significant diversity in their goals, architecture, and capabilities, covering a wide range of functionalities. Basic monitoring systems focus on controlling temperature, humidity, lighting, and the status of doors / windows. They typically use ESP32 as a controller and employ Wi-Fi with the MQTT protocol for communication, which can be connected to a cloud or local server. Their main advantages are low cost and simplicity of implementation, but a significant limitation is their dependence on stable Wi-Fi and an internet connection.

In contrast to basic systems, autonomous security systems extend their functionality to perimeter control, motion detection, and video surveillance. They can use STM32-based controllers in conjunction with ESP32 or Raspberry Pi 4. For sensor communication, Zigbee or Z-Wave are often used, supplemented by LTE/4G for backup communication. Sensors include PIR motion detectors, magnetic door/window sensors, gas sensors, and IP cameras. Such systems are distinguished by their autonomy and high reliability, capable of functioning even without internet access, but their implementation is more expensive and complex to set up [4].

Energy-efficient smart homes aim to optimize energy consumption and automate lighting and heating. They integrate ESP32 with Zigbee coordinators (e.g., CC2531, Sonoff Zigbee Bridge). Sensors such as DS18B20 for temperature, TSL2561 for illumination, and PZEM-004T for power consumption are used. Communication is carried out using Zigbee, Wi-Fi, and MQTT. Such systems often utilize smart relays (Sonoff, Shelly), motorized thermostatic heads, and smart lamps (Philips Hue, Yeelight). Their value lies in reducing electricity costs and providing flexible control, although they require careful configuration to achieve optimal results.

The most comprehensive approach is intelligent automation, which represents a deep level of automation, including voice control and full integration with various IoT devices. These systems often use more powerful controllers, such as Raspberry Pi 4 or x86-based servers, with ESP32 peripherals. They support a full set of sensors (temperature, lighting, CO2, water/gas leaks) and a wide range of communication protocols, including Zigbee, Z-Wave, Matter, and Thread. System control and interaction are implemented through voice assistants (Google Assistant, Alexa) and AI analytics capabilities. Although these systems provide full control and a high level of comfort, they are characterized by significant implementation complexity and high cost [5].

Considering the analyzed limitations of existing approaches, the goal of this work is to develop an integrated monitoring system with an adaptive modular architecture based on the ESP32 microcontroller, which will overcome the identified shortcomings of commercial solutions. Specifically, the emphasis is placed on creating a flexible, scalable, and energy-efficient architecture that uses the ESP-NOW protocol for reliable wireless interaction between components, while ensuring affordable cost and ease of setup. Each module of the system must function autonomously, while maintaining system integrity and effective interaction between components.

To ensure the effectiveness and universality of the developed system, key technical requirements covering the main aspects of its operation were defined. First and foremost, special attention was paid to energy efficiency: the system modules must be characterized by low power consumption, which is critically important for ensuring long-term autonomous operation, especially in the absence of a constant power source. No less important is the compactness of the devices, which involves optimizing their overall dimensions to simplify the integration process into various spatial constraints and environments.

Furthermore, the system must be flexible and scalable, meaning it should be capable of expansion and modernization without the need for complete reconfiguration or alteration of the already implemented architecture. Ease of setup implies the development of an intuitive user interface that allows for parameter configuration without the involvement of highly qualified specialists. An important functional component is also the ability for real-time monitoring, which involves continuous tracking of module operation parameters with data transmission to a central controller or cloud service for operational analysis and decision-making.

Particular emphasis is placed on the requirement for universal interaction with sensors and executive mechanisms, which ensures support for a wide range of external devices. This, in turn, increases the functional adaptability of the system to various operating conditions and scenarios of its practical use. An important aspect of the project is the application of the ESP-NOW wireless protocol, which provides fast data transmission between modules with minimal delays. Unlike traditional Wi-Fi solutions, ESP-NOW does not require a constant connection to a router or cloud services, which reduces maintenance costs and improves the system’s energy efficiency.

3. Research results

The developed system supports two operating modes: automatic and manual. All modules are designed with energy consumption minimization in mind, ensuring long-term autonomous operation even with limited access to the power grid. This is achieved by using energy-efficient components, optimized operating algorithms, and reducing data transmission frequency when environmental parameters remain unchanged.

In the structure of the developed integrated monitoring system, according to the logic of functional division, four main modules are envisioned, each performing specific tasks within the overall system architecture. Specifically, the central module serves as the primary control element of the system. Its functional purpose is to ensure two-way communication with other modules, centralized processing of data received from them, and providing the user with convenient access to information through the built-in interface. The display, integrated into this module, serves for real-time data visualization and simplifies interaction with the system.

The climate control module performs the function of monitoring environmental parameters, including temperature and relative humidity. The collected data is promptly transmitted to the central controller, where it is processed with the possibility of further system response, for example, by controlling air conditioning or ventilation devices.

The motion and lighting module detects motion in the controlled area and determines the level of illumination. Based on the received data, the system can perform intelligent lighting control, changing the intensity of the light flux depending on current conditions and the presence of people in the room, which contributes to energy saving and increased comfort.

The device control module is responsible for implementing executive functions in the system. It ensures communication with peripheral devices and controls them based on commands received from the central module. This realizes the automation of household or technical processes, allowing the system to adapt to various usage scenarios.

The coordinated interaction of these modules ensures the comprehensive functionality of the system, its flexibility, scalability, and adaptability to operating conditions. The functional diagram of the proposed system is presented in Fig. 1.

The selection of the ESP32 microcontroller as the central component of the developed integrated modular monitoring system is justified by a number of its unique technical characteristics and functional advantages, which ensure optimal performance, flexibility, and energy efficiency of the system. The dual-core Tensilica Xtensa LX6 computing architecture with a clock frequency of up to 240 MHz provides the ESP32 with significant computing power. This allows for efficient execution of parallel tasks, including sensor data processing, peripheral device control, and real-time implementation of complex control logic. A key advantage of the ESP32 is its built-in support for Wi-Fi and Bluetooth wireless communication protocols. This is critically important for modular architecture, where wireless data transfer between components forms the basis for implementing a flexible and scalable solution. The ESP-NOW technology is particularly valuable, providing fast and energy-efficient data exchange between multiple devices without the need for deploying external network infrastructure, which reduces latency and increases communication reliability. Additionally, the ESP32 demonstrates high reliability in varying environments due to its extended operating temperature range from –40 °C to +125 °C and built-in self-calibration schemes. These features allow the microcontroller to adapt its operation to current conditions, compensating for potential instabilities of external components. Support for power-saving modes, such as Deep Sleep, is critically important for autonomous power projects, ensuring long-term operation of portable modules or systems with limited energy resources. Finally, the ESP32 stands out for its high level of integration of peripheral interfaces, including up to 48 programmable GPIOs, as well as the presence of UART, SPI, I²C, I²S, PWM, ADC, and DAC. Such diversity ensures universality and compatibility with a wide range of sensors and executive devices, allowing the system to be easily adapted to specific usage conditions and its functionality expanded in the future [6].

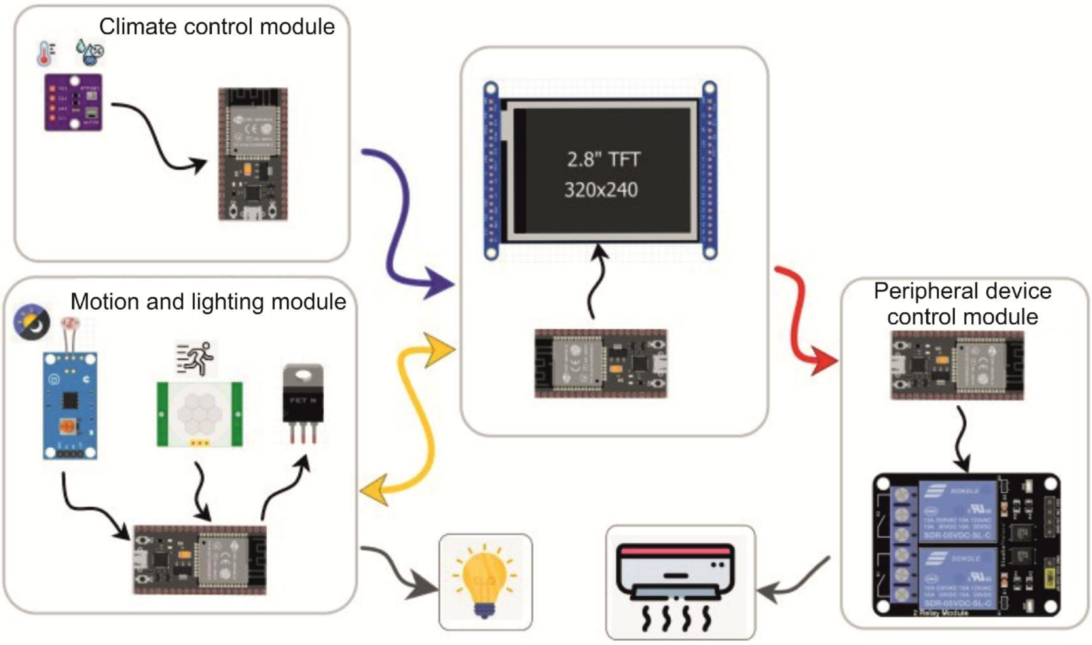


Fig. 1. Functional diagram of the integrated monitoring system

To ensure a convenient and informative user interface in the central module of the system, a touch-sensitive TFT LCD display based on the ILI9341 controller was chosen. This display has a resolution of 240×320 pixels, allowing for the creation of clear and vivid graphical interfaces. A key advantage of the selected display is its support for touch control, ensuring direct interaction with the user. The presence of an SD card slot allows for efficient use of external storage for storing and loading graphical elements, configurations, or other large volumes of data [7]. This frees up limited microcontroller memory resources and expands the functional capabilities of information display. The implementation of connecting the TFT display to the central module via the SPI interface significantly simplified its setup and operation. As shown in Fig. 2, this minimized the number of required input/output ports of the ESP32 microcontroller.

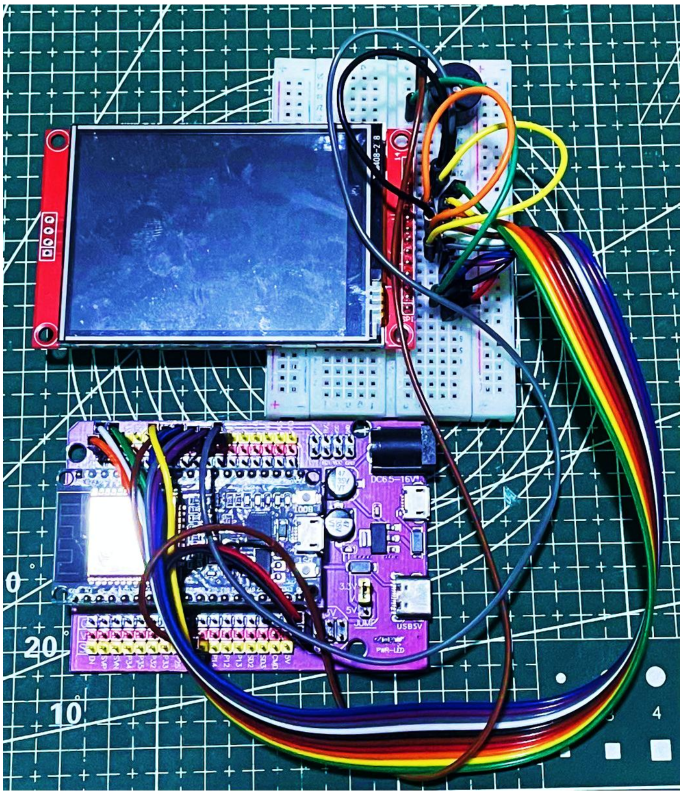


Fig. 2. Implementation of connecting a TFT display to an ESP32 microcontroller

For the climate control module, the digital combined sensor BME280 was chosen, which allows accurate measurement of humidity, pressure, and temperature. This sensor is based on proven measurement principles (capacitive for humidity, piezoresistive for temperature and pressure), ensuring high measurement accuracy (temperature error ±0.5–1 °C, humidity ±3 %). Thanks to its small dimensions and low average current consumption (3.6 µA in active mode and 0.1 µA in sleep mode), the BME280 is excellent for battery-powered devices, meeting the energy efficiency requirements of the modular system. Due to its support for I^2C/SPI interfaces and a wide range of operating temperatures (from −40 °C to +85 °C) and pressures (from 300 to 1100 hPa), the BME280 sensor ensures flexible integration and reliable operation in various environmental conditions [8].

To implement the functionality of motion detection and lighting monitoring in the system, the PIR motion sensor HC-SR501 and the photoresistor KY-018 were selected. The PIR motion sensor HC-SR501 is a versatile component that effectively tracks changes in infrared radiation for presence detection. Its key advantages include a wide sensitivity range (up to 7 meters and 120 degrees) and the ability to adjust the motion detection time (from 3 seconds to 5 minutes).

The photoresistor KY-018 is used to measure the intensity of ambient light. Its operating principle is based on the change in resistance depending on light brightness, which allows for accurate determination of illumination level using a voltage divider. Compact size and operating voltage from 3.3 V to 5 V make it ideal for integration into the module, providing accurate data for automated lighting control [9].

For efficient and reliable wireless data transmission between the system's modular components, the ESP-NOW protocol was chosen. This is a wireless communication protocol developed by Espressif, which enables direct data exchange between ESP32 microcontrollers without the need to connect to a traditional Wi-Fi network or router. Each module uses its unique MAC address for addressed message transmission, allowing the central module to correctly identify the information source (e. g., climate module, motion module, or peripheral control module) and ensure accurate data processing (Fig. 3).

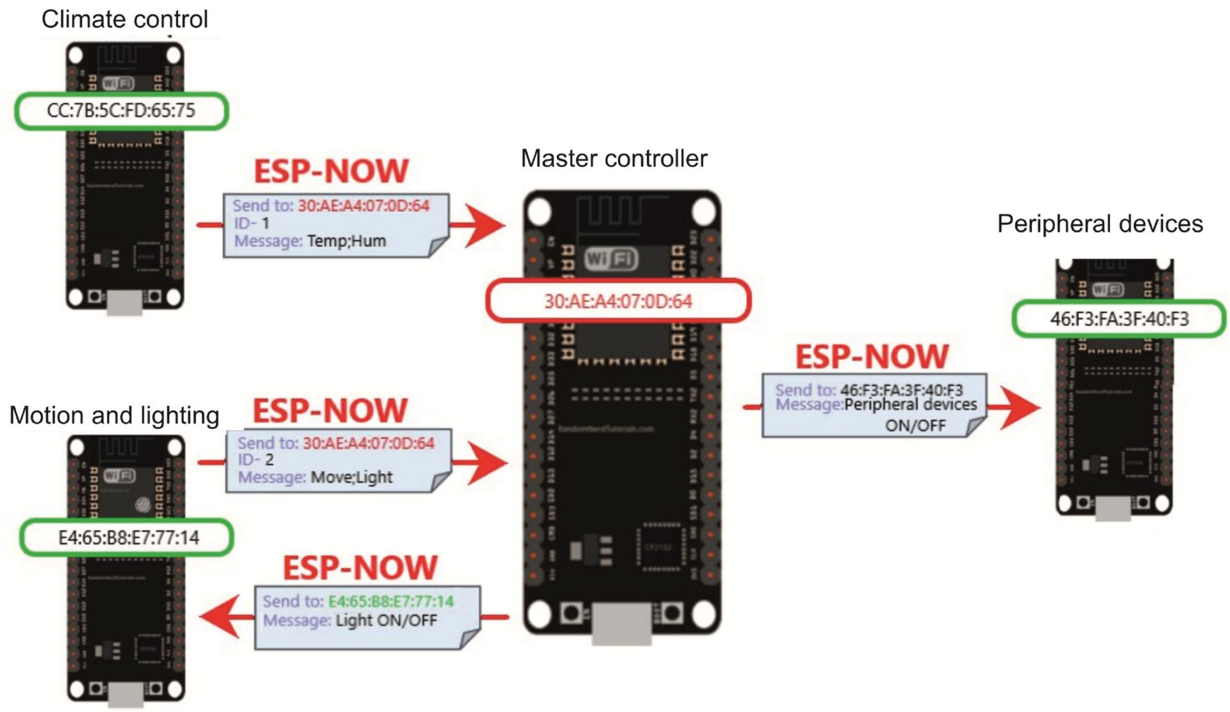


Fig. 3. Diagram of wireless interaction of modules using the ESP-NOW protocol

ESP-NOW is optimized for transmitting small volumes of data (up to 250 bytes) with minimal delays, which is critically important for systems requiring a quick response to changes in environmental parameters or operational control commands. The protocol supports multi-point communication, allowing one ESP32 device to establish up to 20 simultaneous connections (with or without encryption). This ensures the system's scalability and the ability to connect a large number of modules without the complexity associated with setting up traditional network infrastructure. The protocol supports AES-128 encryption, which allows for the protection of confidential and critical data during transmission, increasing the overall level of information security of the system.

Thus, ESP-NOW is a simple, reliable, energy-efficient, and flexible solution for creating a local wireless network in a home monitoring system, ensuring stable and fast data exchange between all its modular components without dependence on external network resources.

The functioning of the developed modular monitoring system is based on cyclical interaction between sensor modules, the central controller, and executive mechanisms, ensuring environmental parameter monitoring, data processing, and adaptive control. The process begins with data collection from sensors: the climate control module continuously monitors changes in temperature and humidity, the motion module detects movement in the coverage area, and the photoresistor tracks the illumination level. Each of these sensors, integrated with its microcontroller, performs primary data processing and transmits it to the central controller.

At the data processing stage, the central controller receives and analyzes information from all sensor modules. Based on this data and established algorithms, it makes decisions regarding the activation or deactivation of the system's executive elements.

Next, interaction with the executive elements occurs: in response to changes in conditions (e. g., motion detection or exceeding a set humidity level), the central controller generates commands. These commands are sent to the relay module for switching electrical appliances on / off, as well as to the MOSFET transistor for regulating lighting brightness. The system provides for both an automatic lighting control mode based on photoresistor data and the possibility of manual brightness adjustment by the user. The final stage is visualization and control, carried out through the central module's touch screen. The display shows current environmental parameters (temperature, humidity, system status) and provides the user with an intuitive interface for interaction. Thanks to the touch interface, the user can change system settings and promptly receive feedback on the status of connected devices, ensuring flexible control and immediate response to parameter changes in real-time. Fig. 4 shows the block diagram of the central module's operation algorithm.

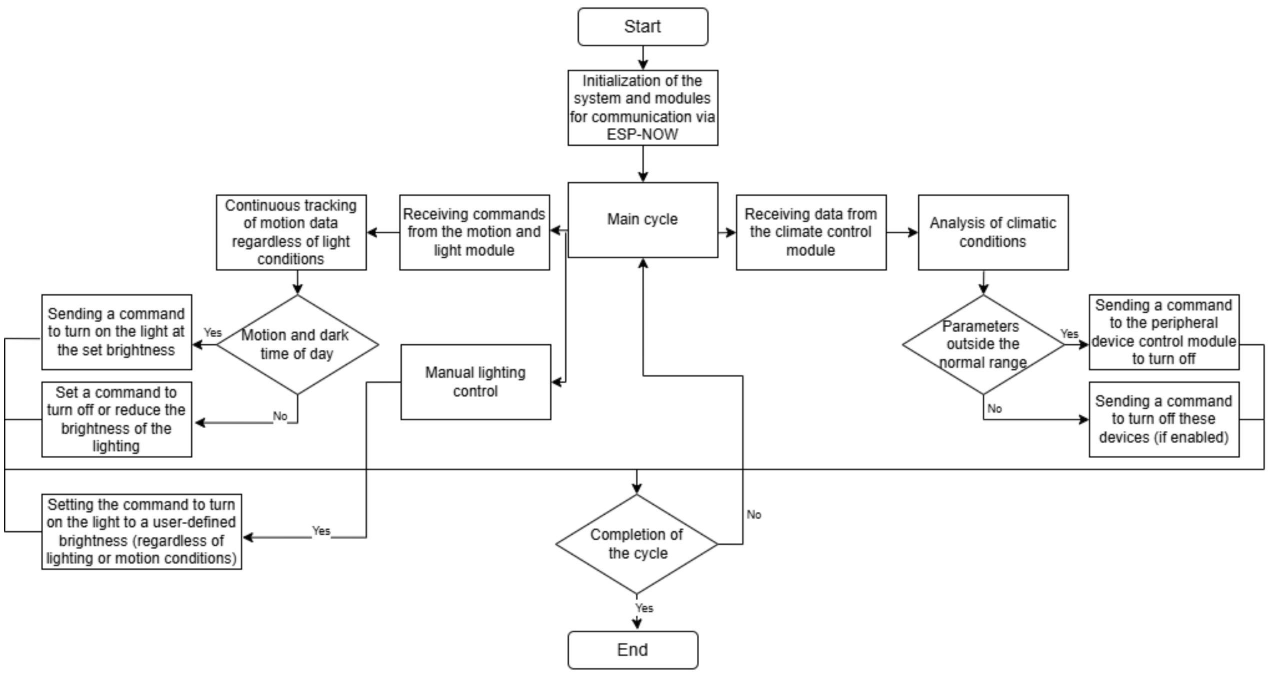
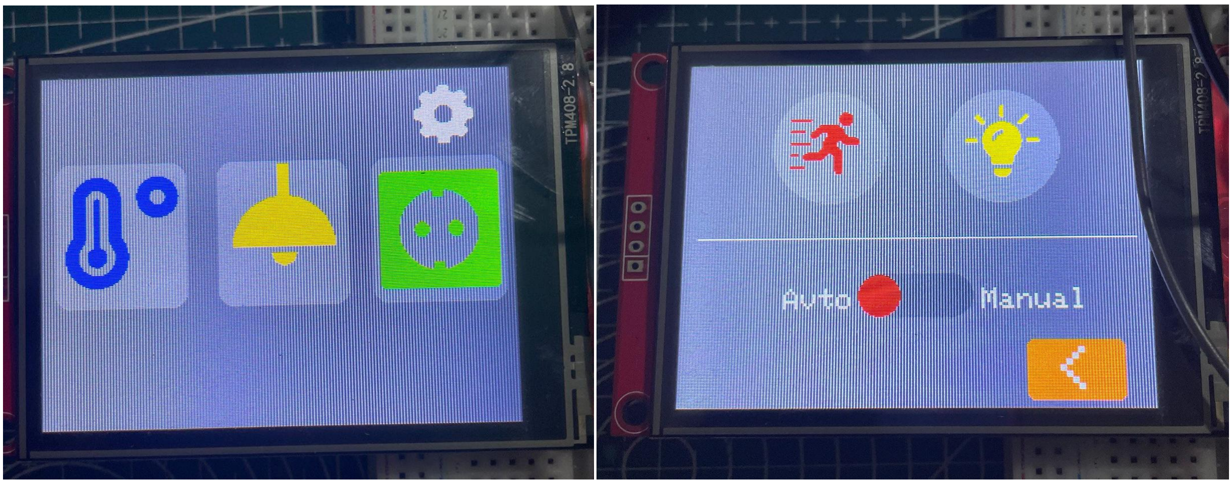


Fig. 4. Block diagram of the central module operation algorithm

Upon system activation, the user is presented with the main screen interface (Fig. 5, *a*), which provides intuitive navigation and access to functional sections. It displays four main icons, each corresponding to a separate module or system function. Specifically, these include icons for accessing indoor temperature and humidity parameters, monitoring motion detection and controlling illumination levels. There are also icons for managing connected external devices and accessing system settings for configuration. This interface structure is aimed at maximizing user convenience and interaction efficiency with the monitoring system.

The lighting control system is implemented with support for two main modes: automatic and manual, ensuring flexibility and adaptability to user needs. In automatic mode, the system autonomously regulates lighting based on the analysis of data received from relevant sensors. Specifically, if the illumination level in the room is insufficient and motion is simultaneously detected, the lamp automatically turns on. Conversely, if the lighting is sufficient or there is no motion, the lamp remains off. The display interface shows an indication of the activated automatic mode and the current status of motion detection (Fig. 5, *b*). Manual mode provides the user with the ability to directly control lighting, regardless of sensor readings. On the touch display, the user can manually turn the lighting on or off. This allows for individual control over lighting, for example, keeping the lamp on even in the absence of motion, which satisfies specific user requirements.

Thus, the implemented main sections of the system provide the user with an intuitive and effective interface for monitoring and managing various aspects of the home environment.



a *b*

Fig. 4. User interface of the central unit: main screen (a), "Motion and illumination" window when motion is detected (b)

Conclusion

In the framework of the conducted research, an integrated monitoring system was developed, which is based on an adaptive modular architecture and utilizes wireless interaction via the ESP-NOW protocol. Experimental results confirmed that the proposed system effectively implements climate parameter monitoring, lighting control, and peripheral device management.

The application of the ESP-NOW protocol ensured stable and energy-efficient communication between all components, which significantly increased the overall operational efficiency of the system. The modular architecture, consisting of a central module, a climate control module, a motion and lighting module, and a peripheral device control module, provides a high level of flexibility. This allows for easy adaptation of the system to individual user needs and the expansion of its functional capabilities by adding new modules. The integration of relevant sensors for data collection contributes to the automation of daily processes in the home environment, which positively affects comfort levels and promotes energy consumption optimization. The developed software demonstrated stable operation in real-time conditions, providing users with the ability for both automatic and manual system control.

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РОЗРОБЛЕННЯ ІНТЕГРОВАНОЇ СИСТЕМИ МОНІТОРИНГУ З АДАПТИВНОЮ МОДУЛЬНОЮ АРХІТЕКТУРОЮ ТА БЕЗДРОТОВОЮ ВЗАЄМОДІЄЮ ESP-NOW

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Описано розроблення інтегрованої системи моніторингу та керування параметрами житлового середовища, яка ґрунтується на мікроконтролері ESP32 та протоколі бездротової взаємодії ESP-NOW. Запропонована система вирізняється адаптивною архітектурою з чітко визначеною модульною структурою, що забезпечує гнучкість, масштабованість та зручність експлуатації. Обґрунтовано вибір мікроконтролера ESP32 як центрального елемента системи завдяки його високій продуктивності, енергоефективності, наявності широкого спектра периферійних інтерфейсів і підтримці бездротового зв'язку Wi-Fi, Bluetooth та ESP-NOW. Ця технологія є ключовою для модульної архітектури, забезпечуючи високошвидкісний, стабільний та енергоефективний обмін даними між компонентами, завдяки чому немає потреби у у зовнішньому маршрутизаторі або хмарних сервісах. Описано функціональні особливості та взаємодію кожного із чотирьох основних модулів: центрального контролера, що здійснює комплексне опрацювання даних та забезпечує користувацький інтерфейс; модуля клімат-контролю, відповідального за точний моніторинг температури та відносної вологості; модуля контролю руху й освітленості, що детектує наявність та регулює інтенсивність світла; та модуля керування периферійними пристроями, призначеного для автоматизації зовнішнього обладнання. Особливу увагу звернено на реалізацію швидкого та енергоощадного бездротового передавання даних, а також побудову інтуїтивного користувацького інтерфейсу на сенсорному TFT-дисплеї. Цей інтерфейс дає змогу здійснювати керування системою як в повністю автоматичному, так і в ручному режимах, надаючи користувачеві повний контроль та можливість персоналізації.
Результати всебічного експериментального дослідження, здійсненого на реальному прототипі системи, переконливо демонструють її високу ефективність у моніторингу кліматичних параметрів, автоматичному регулюванні освітлення та надійному керуванні зовнішніми пристроями. Інтегровані розумні системи такого типу забезпечують вагомий внесок у підвищення рівня комфорту мешканців, оптимізацію споживання енергоресурсів та забезпечення раціонального використання простору за рахунок індивідуальної адаптації функціоналу до потреб користувача.

Ключові слова: *модульна система, домашній моніторинг, мікроконтролер ESP32, ESP-NOW, енергоефективність.*