Integration of edge devices and IoT to create a climate monitoring system for plants

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Abstract

The development of the Internet of Things (IoT) and peripheral equipment is a characteristic feature of modern times. Devices with IoT elements play an essential role in modern life due to their high efficiency, automation and control capabilities in various fields of activity. The MQTT (Message Queuing Telemetry Transport) messaging protocol ensures efficient and reliable communication between IoT devices. Technologies based on this protocol allow for real-time data analysis and processing, which contributes to informed decision-making with high productivity. Plants play a significant role in ensuring positive physical and emotional health. The presence of plants in a room affects a person's psychological state, reducing stress and increasing productivity. In order to ensure an adequate level of psycho-emotional well-being, it is necessary to pay considerable attention to plant care. It has been proven that healthy and well-groomed plants are much more effective in neutralising stressful conditions than those that do not receive the necessary care. Therefore, in this paper, the problem of round-the-clock care for indoor plants is solved by developing an autonomous IoT system. The system's functionality is based on peripheral equipment, allowing monitoring and controlling key climate parameters such as temperature, humidity, and lighting. These parameters are recorded on a remote server for further processing in a mobile application. This paper presents the principles of building a plant microclimate monitoring system, outlines the requirements for the system, the criteria for selecting tools for development, and the technical characteristics of the components. It also describes the structure of the device developed by the author for measuring plant parameters.

Keywords

IoT, MQTT, edge device, automation, data analytics, monitoring, mobile application

1. Introduction

Given that many work industries have fully or partially switched to online mode in recent years, the issue of providing comfortable conditions for remote work has become particularly relevant. Lack of interaction with nature negatively affects employees' physical and mental health [1]. Integrating plants into home offices contributes to increased job satisfaction and overall well-being of employees [1, 2].

The emotional passion for plants is built into the biological nature of humanity, which persists even when people prefer a modern urban lifestyle separated from natural conditions [2]. This is especially important for those who work indoors and require a high level of concentration, as plants can improve the acoustic properties of a room by reducing noise levels [3]. In addition, the presence of green spaces in the work environment helps improve memory and speed decision-making [3, 4]. This effect can be explained by reducing stress levels and creating a more favourable atmosphere for work [2].

It is worth noting that to achieve optimal results, plants must be placed in the room and adequately cared for. Keeping statistics on plant development, including controlling temperature, humidity, and

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lighting, is essential in creating a favourable working environment. This approach will allow you to maximise the potential of plants to improve employee productivity and health.

Recently, the development of tools and technical solutions has made it possible to create plant monitoring systems with advanced functionality. These systems can also transmit climate data to cloud servers for storage, analysis and remote monitoring of these parameters using applications.

At the same time, the rapid development of Internet of Things (IoT) technologies is significantly changing various areas of human activity. These technologies enable various devices to be connected to a single network for real-time data exchange. These technologies are being actively implemented in various areas of human activity, including industry, medicine, agriculture, transport and logistics, environment, and energy.

The IoT involves the interaction of devices via the Internet, which allows collecting, processing and exchanging data to automate and optimise various processes. This technology is promising due to its ability to automate care, reduce costs, and create new opportunities for business and everyday life. Among the leading IT companies actively using and developing IoT are such giants as Microsoft, IBM, Cisco, Google, and Amazon. Their innovations in this area contribute to the widespread adoption of IoT solutions in various sectors of the economy, from industry to everyday life, which opens up new horizons for developing technology and improving the quality of life.

1.1. Related work

Chu et al. [5] offer an in-depth analysis of integrating IoT technologies into modern agriculture. They highlight the IoT's significant role in improving agricultural practices and emphasise its potential to revolutionise modern agriculture. Implementations of IoT solutions are also proposed, detailing how technologies such as sensors and cloud computing are being used to monitor and manage agricultural activities more effectively.

MSES GROUP [6] defines greenhouses as controlled environments for growing plants, where temperature, soil moisture, and light intensity must be monitored and regulated to ensure optimal growth conditions. The proposed greenhouse management system based on the IoT allows remote monitoring of all environmental conditions using the esp8266 microcontroller platform. Recommendations are given for creating an automated irrigation system controlled by a soil moisture sensor that activates the pump when a certain humidity threshold is reached, as well as a system for monitoring air humidity and temperature. Theoretical and experimental studies have been conducted on the display of data on a liquid crystal display and the transfer of relevant information to a web platform that allows users to remotely monitor and control conditions in the greenhouse via a web interface or mobile application.

Noye [7] discusses the role of Node.js in the context of IoT and provides examples of how this technology is used to connect devices. The article emphasises that Node.js is suitable for IoT applications, providing asynchronous operations and multithreading, simultaneous connection of multiple users, and real-time data processing. The example of smart home automation described in the article uses Node.js to communicate between IoT devices such as intelligent lamps, thermostats, and security cameras. The author explored the advantages of Node.js, which makes it an essential tool for developing IoT applications.

Lakso et al. [8] describes the development and application of a novel microtensiometer technology for monitoring water status in fruit crops. The microtensiometer is a tiny sensor, measuring just 5x5mm, that can be embedded directly into plant stems to continuously measure stem water potential - a crucial indicator of plant water stress and overall health.

The technology represents a significant advancement in plant monitoring because it provides continuous, real-time measurements of water status directly from the plant stem, rather than relying on indirect methods. The sensor effectively detects daily cycles of water stress and can clearly show the effects of irrigation, enabling growers to optimize their water management practices [8].

Ndunagu et al. [9] discuss the design and implementation of an intelligent irrigation system (SIS) using wireless sensor networks and the IoT platform (figure 1). The methodology includes integrating hardware and software components to make irrigation decisions based on weather forecasts and soil sensor data. The system uses the ThingSpeak and MATLAB platforms to collect, store, analyse, and visualise data. Based on a theoretical and experimental study, the system has shown high efficiency with an accuracy of 97-98%, ensuring the reliability of irrigation management and water conservation, which can help increase agricultural productivity in rural areas.

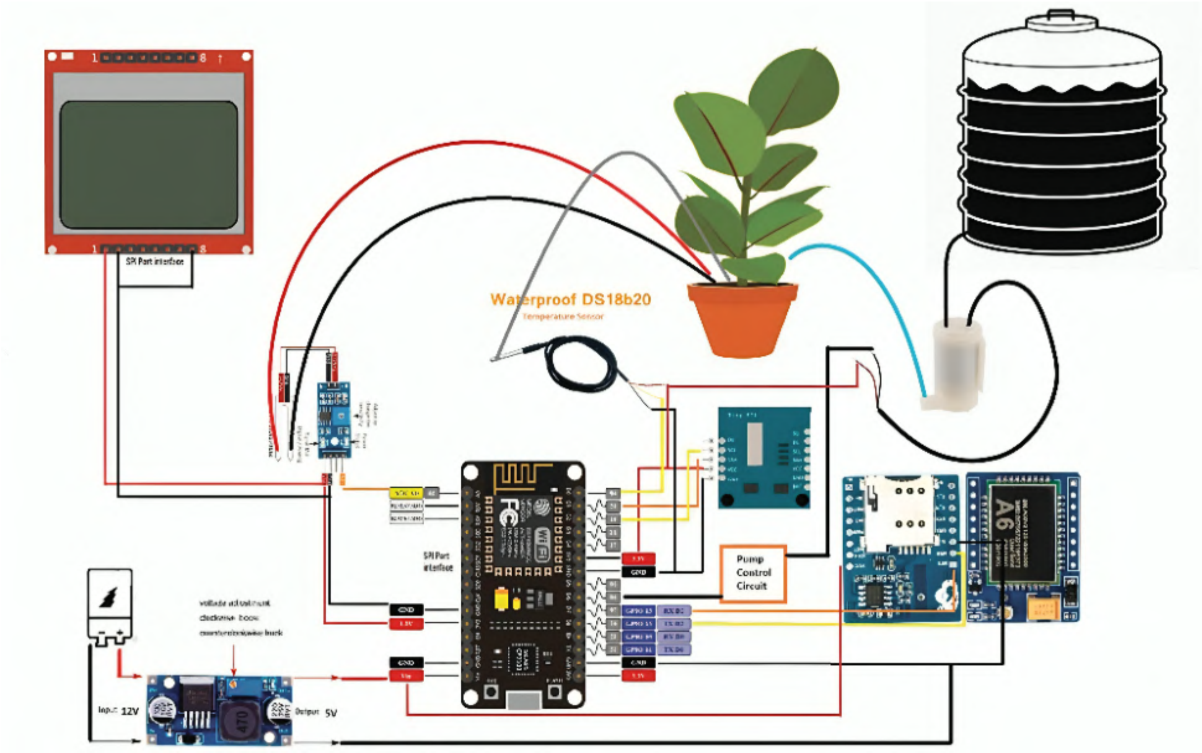

Figure 1: The SIS block and circuit diagram [9].

Kurniawan et al. [10] presented an automated plant irrigation system using the IoT technology and the MQTT protocol (figure 2). The system facilitates plant irrigation by automating the process based on real-time monitoring of environmental parameters such as temperature, air humidity, and soil moisture. The system's main components are a DHT11 temperature sensor, a YL-69 soil moisture sensor, a water pump, and an ESP8266 microcontroller for processing and transmitting information via the Internet. The MQTT protocol is used for efficient communication, allowing users to control the system remotely using mobile devices. The system demonstrates high accuracy, making it a practical solution for today's horticultural needs. This technological advancement reflects the growing trend of integrating intelligent automation into everyday tasks to increase efficiency and convenience.

1.2. Research aim and tasks

The research problem is introducing modern methods and technologies into household plant care to current trends. The idea of the project is to develop a technology model for monitoring climate change during plant development and design and create a corresponding device.

The article describes developing an IoT system for monitoring and controlling indoor plant climatic parameters. This system provides the whole required set of indicators using peripheral devices. This system will allow for a detailed assessment of the impact of climate change on plant growth and development, which is an important factor in maintaining their vital functions.

The purpose of the study should be achieved by solving the following tasks:

- defining the basic concepts and principles of using the Internet of Things;
- development of the software of the modules using the MQTT protocol standard;
- create, test, and customise individual project components.

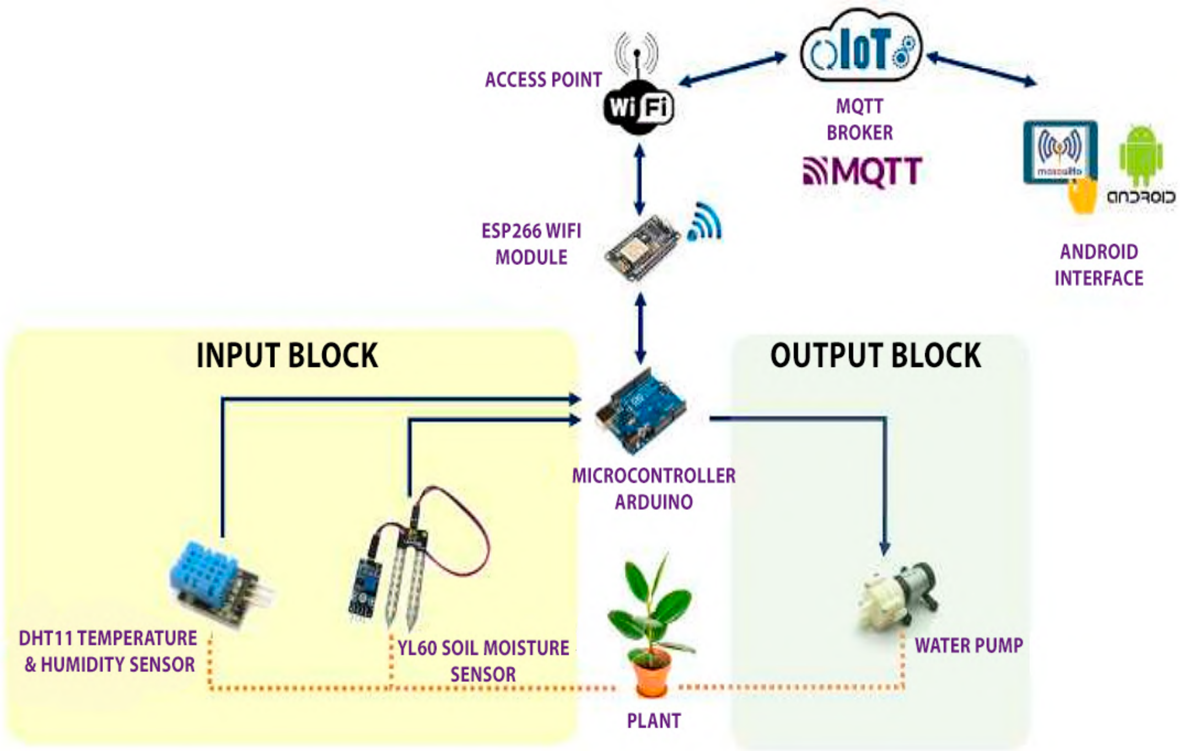

Figure 2: IoT-based brilliant garden design architecture [10].

To achieve this goal, several research methods were involved: theoretical methods, such as analysing scientific and technical sources and generalising and modelling information processes arising in the statistical analysis of plant climate change; research methods, including observation and analysis of the experience of using IoT technologies; and practical methods aimed at developing and testing software.

2. Results

2.1. Exploring the fundamental concepts of the study

The edge device for tracking climatic changes in indoor plants is necessary to ensure optimal conditions for plant growth and development, which contributes to improving their vital functions and decorative properties [11]. The device should be able to monitor the indicators and send notifications in case of their deterioration.

The proposed system is an integral part of an integrated environment. It creates comfortable and productive conditions in various facilities, including educational institutions, offices and residential buildings. A unique feature of this development is the use of devices for monitoring the climatic parameters of indoor plants, with data transmission based on the principles of the MQTT protocol.

MQTT (Message Queuing Telemetry Transport) is a messaging protocol developed for data transmission in resource-constrained environments, such as low-bandwidth networks or devices with limited computing capabilities [12, 13]. MQTT uses a publish-subscribe model, allowing efficient data transfer between devices and ensuring high reliability and minimal energy consumption. The protocol is widely used in IoT systems to communicate between sensors, controllers, and other devices.

The Kafka data streaming platform [14] is an important component of the data exchange architecture in IoT systems, which provides reliable and scalable information transfer between different services. It allows for asynchronous communication and real-time processing of large amounts of data. Thanks to the publish-subscribe model, Kafka can efficiently transmit events from the MQTT service to other services that subscribe to the corresponding events.

Table 1
The functional features of the edge device.

Name	Description
Plant health monitoring	The device constantly monitors the main parameters of the microclimate, providing the user with accurate information about the plants' condition and needs.
Preventing stressful situations for plants	Thanks to the built-in notification system, the device informs the user about the approach to critical conditions that can cause plant stress. This allows you to take timely action to prevent plant damage or disease.
Automation of plant care	The device can integrate with other systems, such as watering or lighting, to adjust care conditions. This reduces the need for manual control and ensures that the plants maintain a stable microclimate.
Promotion of home gardening	The device's ease of use and integration with mobile applications help popularise home gardening. It allows even inexperienced users to successfully care for plants, stimulating interest in growing plants at home.

The collected statistics are used to dynamically display information about plants' states in the application, which provides the necessary tools to create optimal conditions for their development.

Advances in electronic sensors have significantly improved plant monitoring. These sensors can accurately measure various parameters, including temperature, humidity, and light intensity, reducing the need for human intervention. Thermocouples and electronic hygrometers are widely used in greenhouses and research centres.

The functional features of such a device are classified in the following main areas (table 1).

This system is autonomous, thanks to the solar battery. This allows the device to be self-contained without needing a constant connection to the power grid or regular battery replacement. As a result, it is energy efficient and environmentally friendly, which helps to reduce operating costs and minimises environmental impact. The system has built-in sensors that monitor real-time climate parameters, transmitting data to a centralised controller or cloud server for further analysis. This allows you to quickly respond to changes in environmental conditions, maintaining optimal conditions for plant development.

Introducing modern automated climate monitoring systems for indoor plants is critical to ensuring their healthy development and optimal growth conditions. This system can be used with cloud computing and IoT tools in everyday life.

2.2. Constructing a model for an edge device

Our goal was to design a device that can provide highly accurate indicators (for plant health) while maintaining battery life and being easy to use. It provides integration with the IoT through support for the MQTT protocol, which allows continuous interaction with cloud services for data storage and analysis. Figure 3 shows a diagram of the temperature data transmission process using the MQTT protocol.

The application is easy to use, allowing users to configure parameters easily and receive notifications of critical changes in climatic conditions. This contributes to a rapid response and effective management of conditions for plant development. Figure 4 shows a diagram of the components of an edge device.

The main goal of the development was to create a low-cost device, which meant that the entire infrastructure had to be created independently, without the involvement of third-party resources. The central device is a microcontroller that collects the information flow from the sensors and, if necessary, sends this data to the server. A secondary element is a rechargeable battery, as the board cannot operate without it. A solar panel will be installed to reduce the number of charges, which will indirectly act as a light sensor. All data is structured on the server side and recorded in the database. In turn, the user sees

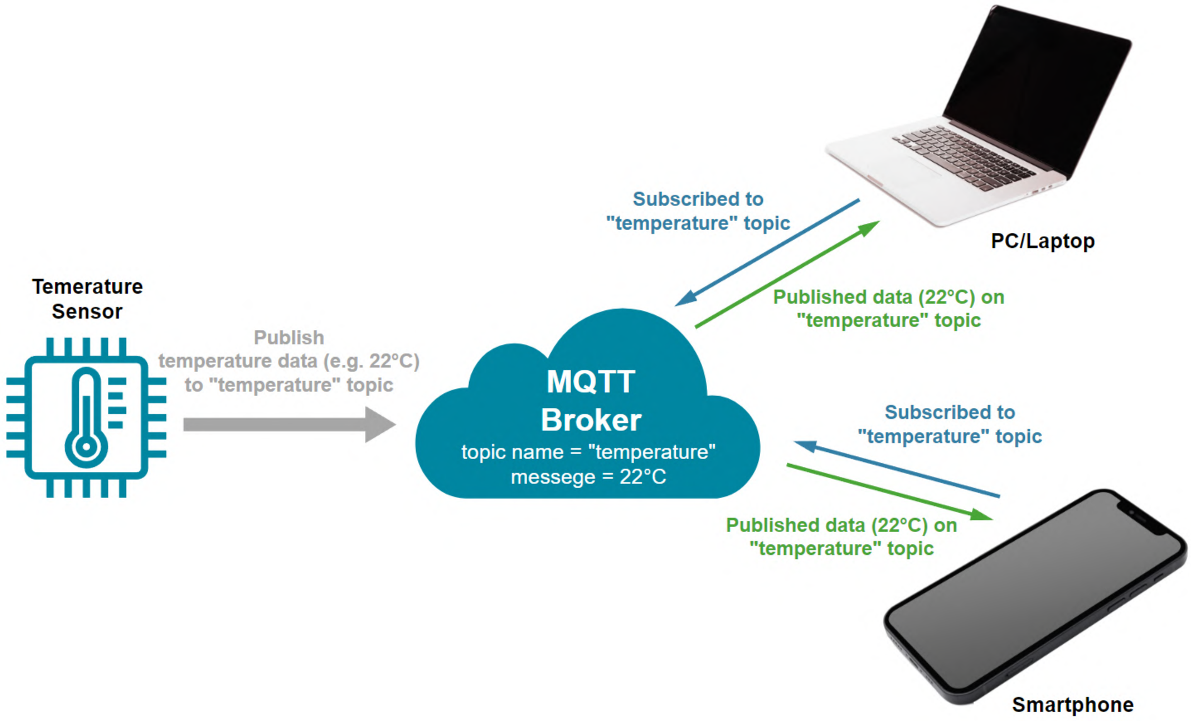

Figure 3: Diagram of the temperature data transfer process using the MQTT protocol.

all the changes on his device and, if necessary, can conduct full analytics for any period.

Each component processes data from sensors according to specific algorithms, which allows for the control and monitoring of climate indicators via mobile devices using an Internet connection. Figure 5 shows a diagram of the system, which is divided into three levels: communication, control, and command.

Various methods are used to develop a plant climate change monitoring device, covering technical, engineering, and design aspects. This enables a detailed analysis of the device's requirements and the selection of optimal materials and components based on their functionality and efficiency.

2.3. Structure and integration of plant monitoring system components

To develop a system for monitoring the condition of indoor plants, a block diagram of the software part of the device was developed. The diagram shows the main components of the system and their interaction. The diagram includes modules for processing, data storage, and user communication, ensuring efficient real-time data transmission. Each component performs the necessary functions within the IoT architecture, providing users with up-to-date information about the plants' state. Figure 6 shows the architecture of the software part of the device.

The system's data lifecycle starts with an edge device equipped with sensors that collect information about the plants' state. When new data is received, the corresponding processor activates a Kafka event, which enables other services subscribed to Kafka to receive and process the information in real-time. This approach ensures that the system responds quickly to changes and increases efficiency.

There are also two services involved in data transfer. The first is the Socket service, which provides real-time updates on the client side, whether a mobile application, an administrative panel, or a website. The service uses WebSockets technology, specifically Socket.io, to transfer data without needing constant requests. As soon as the service receives data from the edge device, it checks to see if a user is currently viewing the data and, if so, notifies them that new updates have arrived, ensuring that the information is interactive and up-to-date. The second service is the tracking service, which stores the received data in the InfluxDB time series database. This is important for analysing the collected data, as it allows you

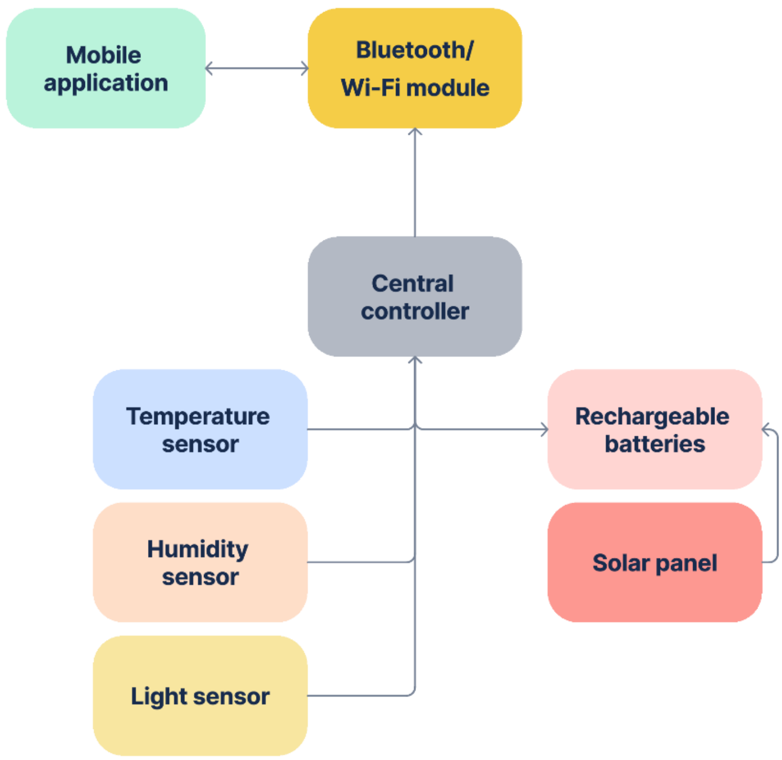

Figure 4: Diagram of the device components.

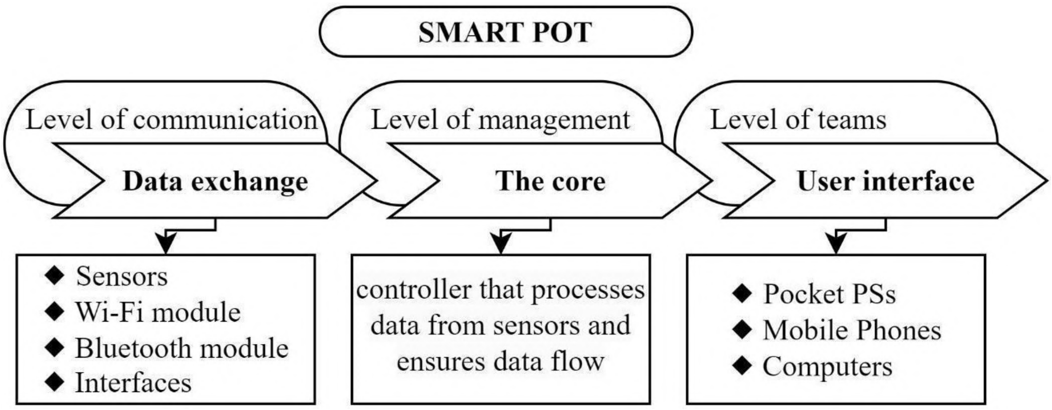

Figure 5: Model of intelligent pot.

to link indicators to a specific edge device through its identifier, which provides the ability to monitor and analyse trends in plant development over the long term.

2.4. System for processing user requests

Our proposed platform will allow collecting, processing, and storing various information about plants and edge devices, their characteristics, and change history. It will also perform user access control operations, which ensures high performance, data integrity, and scalability as the load increases.

User requests are processed through the Gateway API, which coordinates user interaction and the system's internal services. For example, suppose a user requests statistics for a particular asset. In that case, the Gateway API first authorises the request through the Accounts service, checks access

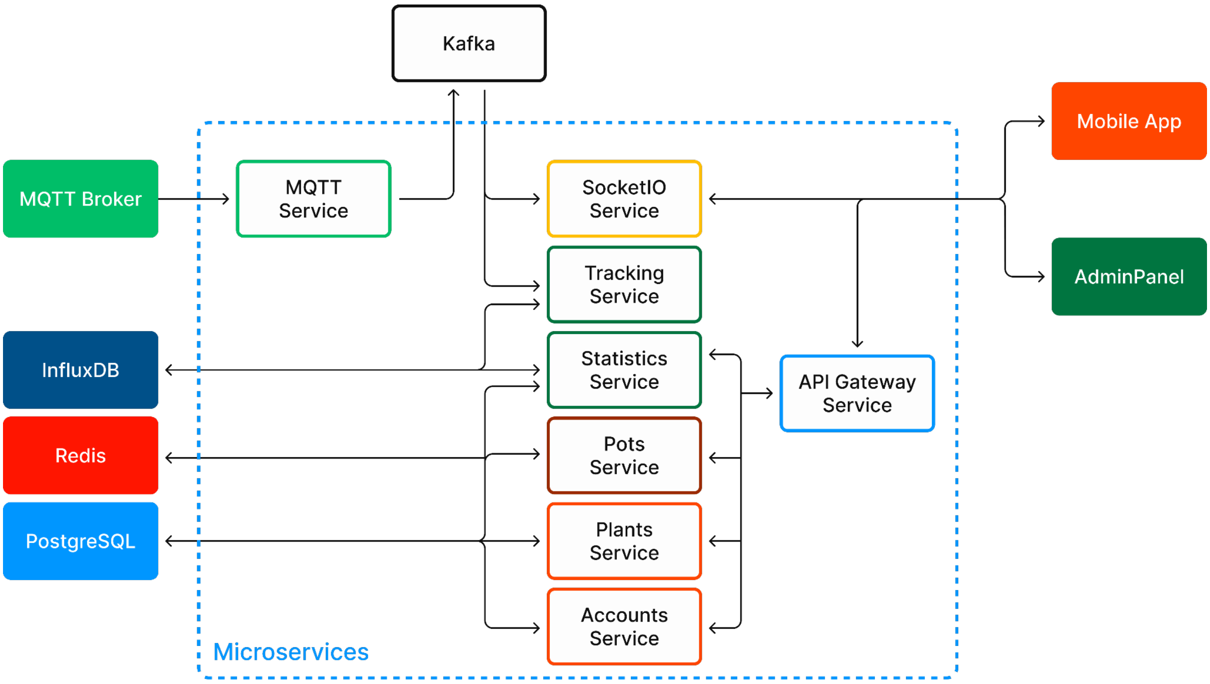

Figure 6: Architecture diagram of the software part of the device.

rights, and then redirects it to the Statistics service, which returns the required data. This multi-level verification ensures the system's security and integrity.

The Statistics service is responsible for processing statistical queries and interacts with databases: PostgreSQL for storing master data, InfluxDB for time series, and Redis for caching, which improves the system's overall performance.

The Plant service manages operations with edge devices and plants, such as adding, removing, linking, and editing. It provides a connection between physical pots and virtual plants in the system, allowing users to manage their plants effectively through the app.

Edge devices are added to the system by an administrator or automatically. They can then be linked to a plant by scanning a QR code or entering an identifier, allowing for precise matching between the plant and the readings from a specific edge device.

All microservices are implemented on the Node.js platform and interact with each other using the gRPC protocol, as standard HTTP requests may not be efficient enough for the required operations.

The front end includes a React-based administrative panel for system management and a progressive web application (PWA) for clients, which simplifies development and testing and reduces the cost of publishing to app stores.

2.5. Diagram of the edge device SQL

Figure 7 shows a database diagram demonstrating the relationship between the tables. The diagram also shows the fields and methods of the tables that will be implemented in the application to process data from the edge device.

The proposed database scheme for the software part of a plant care device presents a structure that provides storage of data of users, their roles, and permissions, as well as on plants and the edge device. The system's basis is the user table, which contains information about users, including their names, surnames, email addresses, and passwords. This table identifies user access to the system and is linked to the user_role and plant tables.

The role table defines the roles available in the system and describes the rights and responsibilities of each role, which may be necessary to provide different levels of access to the instrument's functionality. The permission and role_permission tables configure access rights in more detail. Permission contains

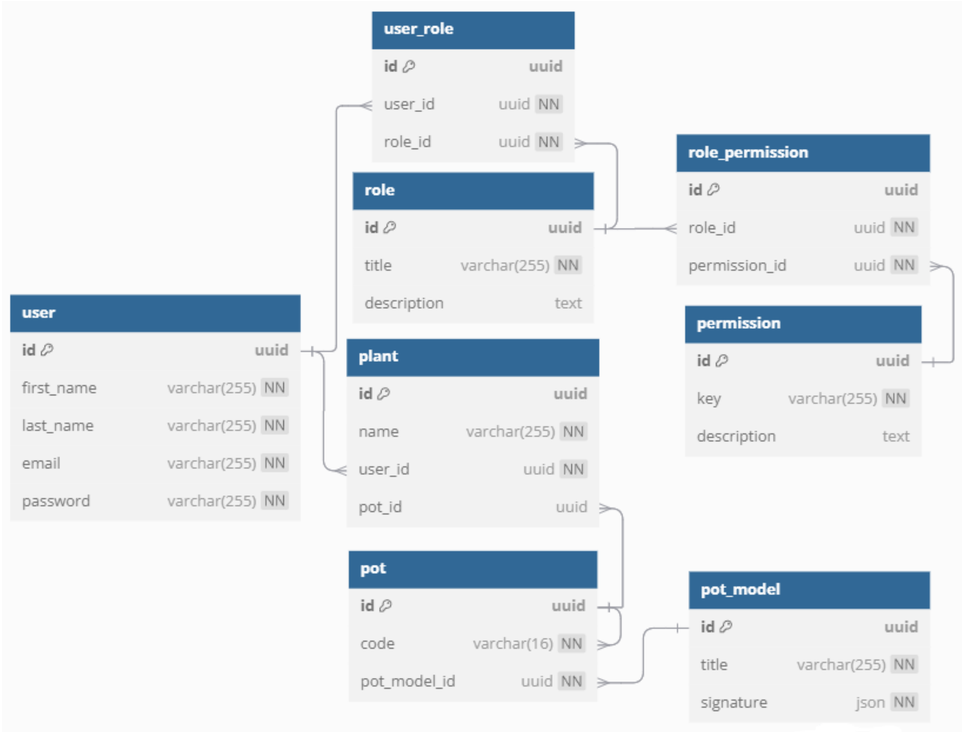

Figure 7: SQL diagram.

a list of individual permissions with a description of each, and the role_permission table provides a link between roles and permissions, allowing you to configure access rights for each role dynamically.

In addition to user data, the database stores information about plants and edge devices. The plant table stores the name of each plant and is linked to the user table through the user_id to identify the owner of a particular plant. An important component is the pot table, which contains information about edge devices, including their unique code and the relationship to the edge device model represented in the pot_model table. The pot_model table contains the model name and signature stored in JSON format, which allows you to store the specifications and configuration of each edge device model. This database structure organises user access to the device and stores data about plants and their containers.

3. Client app prototype

A prototype client application was created based on the described structure and requirements.

The application receives data from sensors installed in the edge device that record soil moisture, temperature, light, and other parameters. Its purpose is to provide users with a convenient tool for visualising data, analysing plant health, and receiving timely care recommendations. Thanks to its intuitive interface, the app is suitable for both experienced gardeners and beginners who want to improve their plant care.

The first page of the web application is the login page, which provides users access to the system. The next page, the registration page, is designed to create a new user account. It contains six input fields: “Last name”, “First name”, “Email”, “Password”, and “Password reset”.

Below the input fields is the “Register” button, which confirms the filled-in data and creates an account. To ensure compliance with privacy and communication standards, the page includes two confirmations: Acceptance of the privacy policy—the user must confirm that he or she has read the terms of data use; and Acceptance of receiving emails from the company—an optional checkbox that allows the user to receive updates, news, or recommendations from the developers.

After logging in to the account, users are taken to the main menu of the web application, which serves as a central hub for interacting with all system functions. This menu provides convenient access to the main sections of the application. First, users can edit their accounts by changing their data.

One key sub-menus is the “My Plants” section, which gives users access to all the pots linked to their account. Here, you can find detailed information about each plant. In the same section, the button “Add plant” opens the menu for adding a new plant, where the user enters the necessary data about the plant.

In addition, the main menu has a submenu called “‘More” that includes additional features. Here, you can view reviews from other users who share their experience using the app or caring for plants. There is also a section for contacting the support team, where you can get help or answers to your questions through the feedback form. The submenus also include app settings that allow you to change the interface language, customise the app’s appearance, or activate additional features.

The footer at the bottom of the application has two function buttons. The first one allows the user to scan the QR code on the edge device to quickly add it to the system. The second button allows you to go to the current page of the main menu. Figure 8 shows the system’s main page.

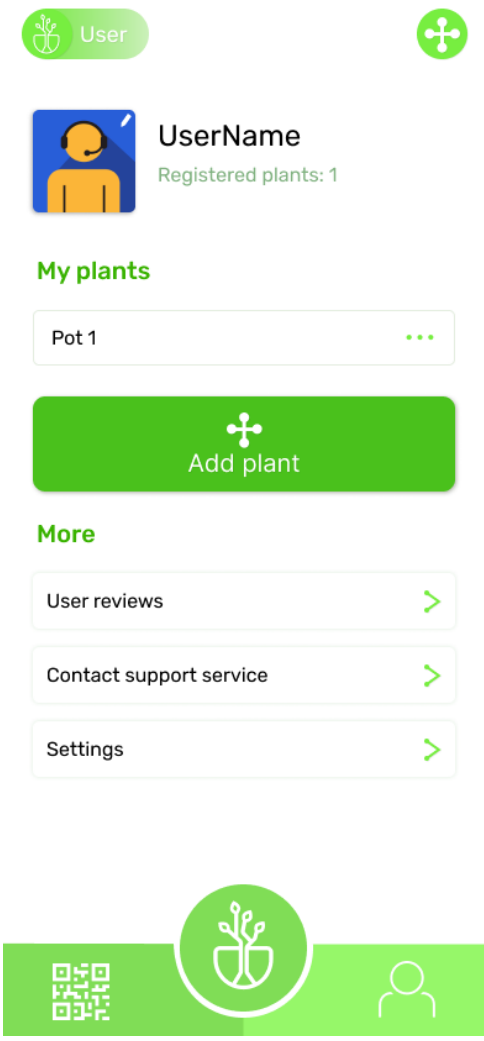

Figure 8: Main page.

After clicking the “Add plant” button (figure 8), a page opens that allows you to configure a new plant in the system. At the top of the page is a field for entering the plant name, where the user can specify the desired name for identification. Below is a section for selecting a plant photo. The user can upload an image from their device or use the built-in camera to create a photo instantly.

In addition, the page includes a drop-down list where you can select the type of plant from the list of available options. The list includes popular categories such as indoor flowers, succulents, or herbaceous plants, allowing the system to automatically adapt care and parameter control recommendations for each type. Figure 9 shows the page for adding a plant to the system.

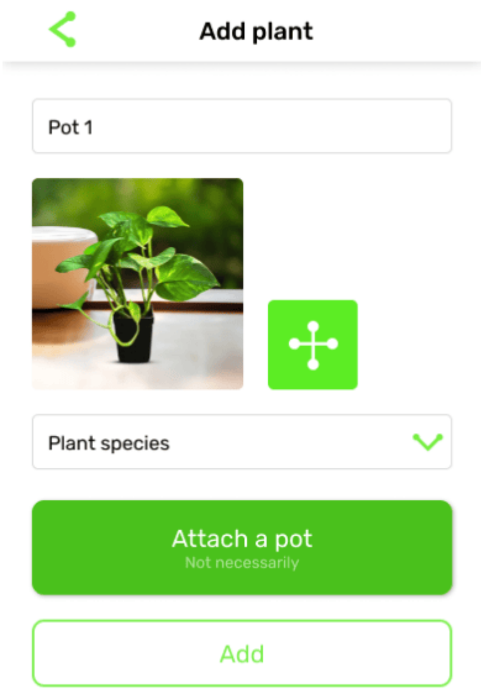

Figure 9: Page for adding a plant to the system.

The user can bind the device to the plant, although this is not mandatory. An additional menu opens to select the connection method to bind an edge device. The system offers two main options: connection via Bluetooth or by scanning the QR code on the device. Figure 10 shows the page for selecting the type of device connection.

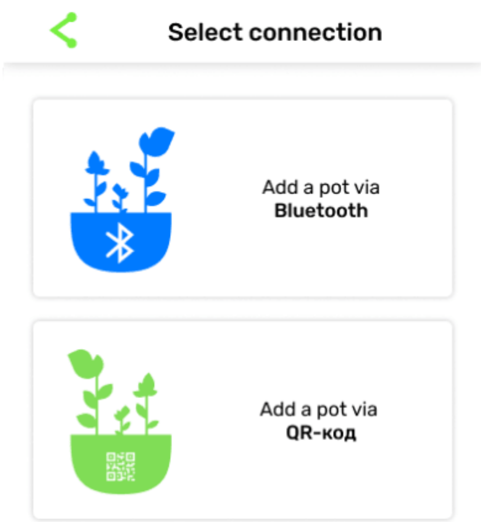

Figure 10: Types of connection of the device to the system.

When Bluetooth is selected, the user is shown a list of available nearby connected devices. If a QR code is selected, the camera is activated to scan it, and the data is automatically synchronised with the app. Figure 11 shows the process of connecting the device via a QR code.

Figure 11: Process of connecting the device via QR code.

The first page of the plant serves as a dashboard that allows you to quickly get a general overview of the status of a particular plant attached to the edge device. At the top of the page is the plant's name, and below the name is a photo of the plant.

To the right of the photo, there is a block of current plant statistics that displays the main parameters of the plant, such as temperature, battery level, light level, and soil moisture. These parameters are displayed as clear icons with accompanying numerical values and colour indications. Figure 12 shows a summary page about the edge device and the plant.

When you click on the block with information about the plant, you are taken to the plant profile, a page with extended information about the edge device. At the top is a field for editing the current plant. Below the field for editing the plant record is an enlarged version of the photo for convenience. Figure 13 shows the editing block for displaying a plant in the application.

The next block is an interactive visualisation of the plant's condition, made in the form of a scale with three zones: green, yellow and red, where the green zone corresponds to the optimal condition of the plant; the yellow zone signals possible problems, reminding you to pay attention to the plant; the red zone demonstrates the critical condition of the plant, focusing on immediate actions to save the plant. This scale works based on collected data on the plant's condition, where each parameter is taken into account in the overall score that determines the position of the indicator on the scale. Figure 14 shows the plant health visualisation block.

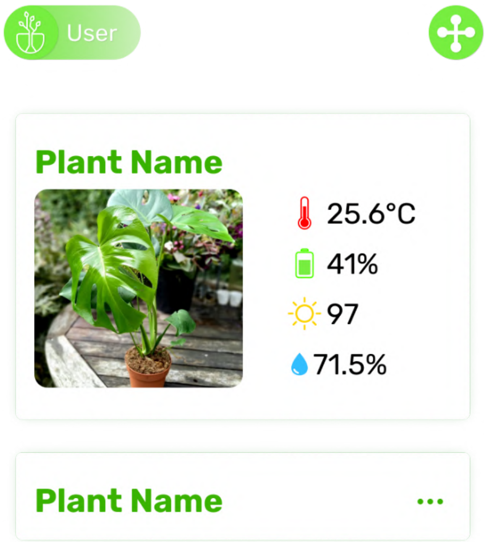

Figure 12: Summary page about the edge device.

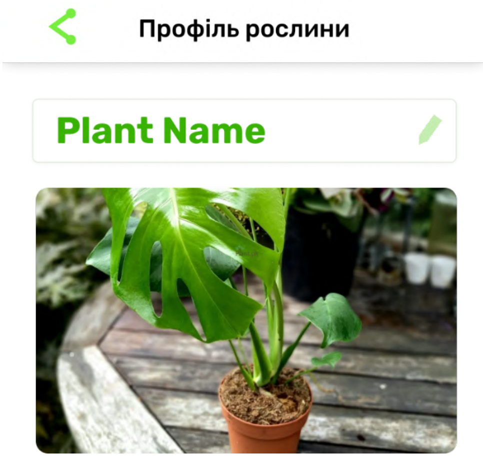

Figure 13: Submenu for editing the plant display in the application.

Figure 14: Plant condition visualisation unit.

Below the plant status scale are visual graphs that provide detailed information on key parameters such as temperature, humidity, lighting and pot battery power. Each graph is designed in an easy-to-read style, with smooth lines showing the dynamics of changes in these parameters throughout the day.

On the left side of each graph are numerical values that show the range of the parameter, such as degrees for temperature or percentages for humidity. At the bottom of the graphs is a timeline covering 24 hours, allowing the user to track changes in real time and over the last period. The graphs are separated from each other to avoid mixing data but are designed in a single style that provides a harmonious look. Figure 15 shows graphs for visualising plant health statistics throughout the day.

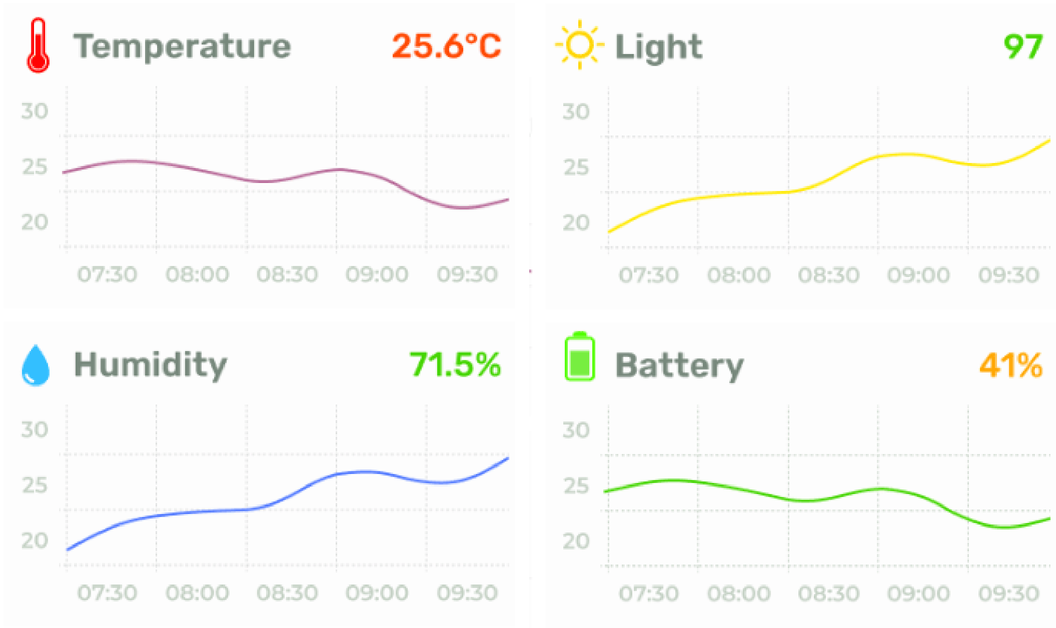

Figure 15: Graphs for visualising plant statistics.

Below the graphs is a unique pot code associated with a particular plant. This code is the device identifier needed to synchronise or reconnect the edge device to the system if necessary.

Below the code is the "Remove device" button, which allows the user to disconnect the device from the current plant. Clicking on this button opens a modal window with a warning.

4. Discussion

Modern electronic sensors can provide high measurement accuracy, there is always a risk of errors due to external factors or component wear. Regular calibration and maintenance are essential to maintain sensors' functionality at a high level.

The use of the MQTT protocol provides efficient data transfer with limited resources, but the security issue of the transmitted information arises. Since MQTT does not provide data protection at the protocol level, it is necessary to implement data encryption and device authentication to prevent possible cyber threats. The device requires a power source for continuous operation. Using a solar panel to power the system autonomously is a significant advantage in terms of environmental safety and reduced operating costs. However, the question arises about the system's efficiency in low-light conditions or rooms with limited access to sunlight. In such cases, alternative power sources or more efficient ways of energy storage should be provided. All these issues encourage further development and improvement of intelligent climate monitoring systems for indoor plants.

The current work's approach to plant monitoring shares similarities with Lakso et al. [8] microtensiometer technology, but differs in scale and application. While Lakso's work focuses on precise stem water potential measurements in commercial fruit crops, this project adapts similar principles for indoor plants using simpler, consumer-grade sensors. The current system's use of multiple parameters (temperature, humidity, light) provides a more comprehensive but less specialized monitoring approach compared to Lakso's focused water potential measurements.

The suggestion to implement Lakso's microtensiometer technology for indoor plants presents an interesting direction for future development. This could bridge the gap between precise agricultural monitoring and consumer applications, potentially leading to more accurate and reliable plant care systems [8].

The system's use of MQTT aligns with Kurniawan et al. [10] approach, but extends beyond their implementation by integrating Kafka for data streaming. This addition creates a more robust architecture for handling real-time data, addressing one of the limitations noted in Kurniawan's work. However, as mentioned in the discussion, this introduces additional security considerations that weren't as prominent in simpler MQTT implementations.

The system's approach to data visualization and user interaction through a mobile application represents an advancement over traditional monitoring systems. Unlike Ndunagu et al. [9] focus on irrigation control, this system provides a more comprehensive interface for general plant care, though it could benefit from incorporating their advanced analytics capabilities.

5. Conclusions

The study of technologies such as MQTT, IoT, React, and NodeJS provided the basis for creating a device for monitoring the plant's climate indicators. MQTT technology has made it possible to implement an efficient data transfer protocol between the sensors and the central server to ensure uninterrupted monitoring. IoT technologies enable the integration of various sensors and devices into a single system, providing an integrated approach to data collection and analysis.

The developed system for monitoring the parameters of indoor plants not only improves the quality of plant care but also demonstrates the capabilities of modern technologies in creating intelligent monitoring and control systems. The research results conducted with this system will provide the conditions for high-quality plant development. The system is currently being tested and improved. The developed device can also monitor plant parameters in closed facilities: offices, schools, shelters, hospitals, house rooms, universities, etc.

Author Contributions: Conceptualization – Nikita S. Prasol and Denys V. Furikhata; methodology – Tetiana A. Vakaliuk; formulation of tasks, analysis – Denys V. Furikhata and Tetiana A. Vakaliuk; software – Timothy Y. Regenel; embedded development – Timothy Y. Regenel; analysis of results – Denys V. Furikhata and Nikita S. Prasol; visualization – Nikita S. Prasol; writing – original draft – Tetiana A. Vakaliuk and Denys V. Furikhata; writing – review and editing – Tetiana A. Vakaliuk. All authors have read and agreed to the published version of the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analysed during this study. Data sharing is not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Acknowledgments: The research was verified and evaluated in actual conditions with the help of the Faculty of Information and Computer Technologies of the Zhytomyr Polytechnic State University. Thanks to the university's support, the research team had access to the necessary equipment and software, which significantly increased the efficiency of the device development. The authors express their gratitude to the PolyHub scientific group for their valuable contribution to the development of the SmartPot project, which significantly enhanced the device's functionality and practical implementation.

Declaration on Generative AI: The authors have not employed any generative AI tools.

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