Всеукраїнський науково-технічний журнал
Ukrainian Scientific & Technical Journal
ISSN 2306-8744
DOI: 10.37128/2306-8744-2024-2

Вібрації в техніці та технологіях

№2 (113)
2024

Всеукраїнський науково-технічний журнал

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Вінниця 2024

ВІБРАЦІЇ В ТЕХНІЦІ ТА ТЕХНОЛОГІЯХ

Журнал науково-виробничого та навчального спрямування Видавець: Вінницький національний аграрний університет

Заснований у 1994 році під назвою “Вібрації в техніці та технологіях”

Свідоцтво про державну реєстрацію засобів масової інформації

КВ № 16643-5115 ПР від 30.04.2010 р.

Всеукраїнський науково-технічний журнал “Вібрації в техніці та технологіях” / Редколегія: Калетнік Г.М. (головний редактор) та інші. – Вінниця, 2023. – 2 (113) – 142 с.

Друкується за рішенням Вченої ради Вінницького національного аграрного університету (протокол № 2 від 30.08.2024 р.)

Періодичне видання включено до Переліку наукових фахових видань України з технічних наук (Категорія «Б» Наказ Міністерства освіти і науки України від 02.07.2020 р. № 886)

Згідно рішення Національної ради України з питань телебачення та радіомовлення від 25.04.2024 р. № 1337 науковому журналу «Вібрації в техніці та технологіях» присвоєно ідентифікатор медіа R30-05172.

- присвоєно ідентифікатор цифрового об’єкта (Digital Object Identifier – DOI);

- індексується в CrossRef, Google Scholar;

- індексується в міжнародній наукометричній базі Index Copernicus Value з 2018 року.

Адреса редакції: 21008, Вінниця, вул. Сонячна 3, Вінницький національний аграрний університет, тел. 46 – 00– 03

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УДК 621.311.2:631.6
DOI: 10.37128/2306-8744-2024-2-13

INTEGRATION OF SENSOR TECHNOLOGIES INTO THE STRUCTURAL SCHEME OF AUTOMATED GREENHOUSE CONTROL

The development of wireless sensor network technologies has opened up new opportunities for monitoring and controlling greenhouse parameters in precision agriculture. Over the past decades, significant advances in agricultural technology have been made, which has contributed to higher yields. With the uneven natural distribution of rainwater, it is important for farmers to ensure that water is distributed evenly to all crops on the farm or according to the needs of individual crops. There is no one-size-fits-all irrigation method that is suitable for all weather conditions, soil types, and different crops.

Greenhouse technologies can be the best solution to this problem. Choosing the right method requires a detailed analysis of all greenhouse parameters. Farmers often face large financial losses due to incorrect weather forecasting and the wrong method of irrigating crops.

The aim of the study is to create conditions for increasing the efficiency of growing vegetables in greenhouses by introducing highly integrated systems for control, monitoring, management and automation of production processes. This involves the development of a structural diagram of a mechatronic smart system for monitoring and dispatching technological processes.

As a result of the research, a flowchart for automated greenhouse control was developed. In this scheme, the adaptation unit, based on the obtained values of environmental parameters, compares them with the standard values. If deviations are detected, the system sends information signals to adjust the agroclimatic conditions by activating the appropriate actuators - humidifiers, lighting lamps, internal irrigation and heating systems.

Keywords: *hydroponics, energy efficiency, productivity, lighting, greenhouse, plant cultivation, vegetation, photosynthesis, plant nutrition*

Introduction. The need to increase the efficiency of agricultural enterprises leads to the introduction of modern technical solutions based on the use of high-tech systems for control, monitoring, management and automation of production processes. The key components of this approach are a wide range of technologies, such as global positioning systems, control systems, sensor control and monitoring systems, robotic systems, unmanned aerial vehicles, highly integrated smart systems and artificial intelligence systems.

Traditional crop production involves the systematic collection and analysis of agro-ecological indicators to make management decisions on agrotechnical practices and create favorable conditions for plant development. This includes controlling temperature, soil and environmental moisture, light intensity, weediness of the site, and the degree of pest or disease damage. Greenhouse farming is more flexible in terms of control and management, as it is a system where plants are grown in an artificially created ecosystem environment.

In precision agriculture (PA), there are various methods for monitoring and controlling important environmental parameters required for specific crops.

Particular attention should be paid to methods that effectively maintain optimal environmental conditions. In greenhouse precision farming technologies, wireless sensor networks for large areas are becoming increasingly popular. The number of parameters that need to be monitored in greenhouses is growing every day, which can lead to increased data traffic and overloads in the future. Therefore, wireless sensors using broadband or cognitive radio technologies are the optimal solution for efficient data management and remote control of greenhouses over long distances.

Thanks to the concept of greenhouses, a farmer can grow different crops in different climatic conditions and in different seasons. In the proposed greenhouse design, the farmer can easily maintain the necessary environmental conditions for the crops grown. This requires sensors that measure environmental parameters such as temperature, humidity, CO2 level, etc. All these sensors can be connected to a server or node wirelessly. Such a system is called a wireless sensor network and provides efficient monitoring and control of all environmental parameters in precision agriculture.

Greenhouse automation allows you to control and monitor the main parameters of the ecosystem and is one of the most effective methods of obtaining high-quality agricultural products while minimizing production costs. This includes rational consumption of resources, maintaining moisture and thermal conditions, fighting diseases and pests, etc.

Thus, given the obvious advantages of automation and intellectualization of agriculture, the task of developing highly effective tools for managing the parameters of artificially created ecosystems is becoming increasingly important.

Analysis of recent research and publications. The analysis of known technical solutions for the automation of production processes and technological methods in the agro-industrial complex was carried out using generalization methods and a systematic approach.

Many researchers note that greenhouse technologies have found wide application in agricultural engineering. The integration of wireless sensor networks into greenhouses is a relatively new concept that contributes to the development of precision agriculture. Blackmore et al. noted in 1994 that such systems could be developed to improve the quality of agricultural products through effective soil and environmental monitoring. They also pointed out that in the initial stages of wireless sensor networks (WSNs) development, farmers were reluctant to adopt them because of their high cost. However, technological advances have helped to reduce this cost. In addition to MEMS technology for hardware, satellite sensing, remote sensing, global positioning system, and geographic information systems have also contributed significantly to the overall development.

Beckwith and others worked on the implementation of WSNs in a large vineyard, where 65 sensor nodes were installed to collect pH data. Research on crop management within precision agriculture was also conducted as part of the Lofar Agro project in Europe. This project investigated the correct application of pesticides and environmental changes in real time. For the effective control of crop diseases such as late blight, information collected from weather stations and radio networks proved to be extremely useful.

In developing the functional scheme of the smart monitoring system, the hypothetical and deductive method, as well as general methods of agricultural technology, metrology, electrical engineering, computer science, and electromechanics are used. The developed functional and structural diagram of the mechatronic system is based on the use of Internet technologies, sensors, sensors, equipment power automation devices, and other hardware, which are controlled by the Arduino UNO microcontroller board.

The aim of the research is to create conditions for increasing the efficiency of growing vegetables in greenhouses by introducing highly integrated control, monitoring, management and automation systems for production processes, as well as to develop a structural diagram and algorithms for the operation of a mechatronic smart system for monitoring and dispatching technological processes.

Materials and methods. In general, automated greenhouse control systems consist of stationary integrated units similar in function to those of the greenhouse (see Fig. 1). The main ones include a sensor unit, an adaptation unit, and an actuator unit. The sensor unit contains sensors and other devices that read signals, form information packets, and transmit them to the adaptive control unit. In this unit, the data is structured and processed according to certain algorithms, after which an output signal is generated and transmitted to the system's actuators.

When managing a greenhouse, the main monitoring parameters that affect the creation of favorable conditions for plant growth are temperature, relative humidity of air and soil, and lighting parameters. The main task of such a system is to ensure that all these agroclimatic indicators meet clearly defined agrotechnical requirements.

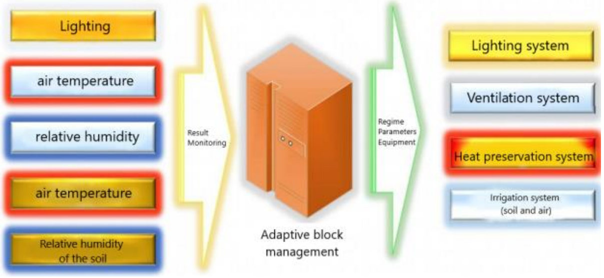

Fig. 1. General structure of the greenhouse management system

Thus, according to the needs and based on the obtained values of environmental parameters, the adaptation unit sends commands to activate the appropriate actuators, such as humidifiers, lighting lamps, in-ground irrigation systems, and heating systems. This helps to ensure the necessary conditions for adjusting agroclimatic factors. In today's environment, when all areas of activity are moving to a high-tech level, the development and improvement of such systems is an extremely promising area of innovation. Significant scientific contributions from both foreign and domestic scientists confirm the feasibility and economic viability of implementing SMART technologies in the most conservative sectors of the economy, in particular in the agro-industrial complex and in growing vegetables in closed ground.

Research results and discussion. The main hardware components of the proposed automation system (see Fig. 2) are the Arduino UNO board based on the ATmega 328 microcontroller and four sensors for supplying input parameters [6]. The microcontroller, in accordance with the downloaded program, reads the input signal from the sensor and generates an output signal. The technical characteristics of the ATmega 328 allow it to read both digital and analog input signals and generate digital outputs. During the operation of the automation system, the microcontroller reads data from the sensors and, depending on their value, generates a digital high/low signal in accordance with the limit values defined in the program. The microcontroller constantly monitors the digitized sensor parameters, compares them with pre-set thresholds, and, if necessary, instantly generates an output signal to activate the actuators (relays, contactors, switches, etc.) used to control the elements of the greenhouse microclimate system (motors, coolers, pumps, lamps, etc.).

Plant growth directly depends on photosynthesis, which in turn is determined by the level of photosynthetically active radiation. Studies show that temperature affects the rate of sugar synthesis during photosynthesis. Therefore, it is important to accurately control the temperature, as increased radiation levels can cause an increase in temperature. During the day, it is necessary to maintain the optimum temperature for photosynthesis, while at night, when plants are less active, high temperatures are not needed. Therefore, two temperature control points are usually considered: day and night.

During the day, the optimum temperature is provided by solar energy. The main problem is the need to cool the greenhouse through natural ventilation to maintain the desired temperature. Nighttime temperature control involves heating the greenhouse to maintain the thermal regime. Heaters are often used for this purpose.

Water vapor inside the greenhouse is critical for crop growth. High humidity can increase the risk of disease and reduce transpiration, while low humidity can cause water stress by closing stomata and reducing photosynthesis by limiting CO2 assimilation. Controlling humidity is challenging because temperature and relative humidity are inversely related.

Temperature and humidity are controlled by the same systems. Temperature control is a priority, as it is the main factor in plant growth. Based on the level of internal humidity, temperature parameters can be adjusted to maintain humidity in the desired range. Thus, humidity control is a complex task. To effectively control the humidity, the internal air can be exchanged with the outside air using greenhouse ventilation systems.

Soil condition also has a significant impact on crop growth. Therefore, monitoring and controlling soil conditions is important to ensure high yields. Watering and fertilization should be appropriate for the type of plant, its age, developmental stage, and climatic conditions. The key parameters are pH, moisture, electrical conductivity and soil temperature. To monitor soil conditions, pH sensors and other parameters are used.

Temperature and humidity can be controlled by drip irrigation and sprinkling systems in greenhouses. Soil temperature and internal greenhouse temperature are closely related and can be controlled by adjusting ventilation. Soil temperature control depends on direct sunlight and the type of screen used. The correct settings allow you to adjust the soil temperature according to the actual temperature readings inside and outside the greenhouse.

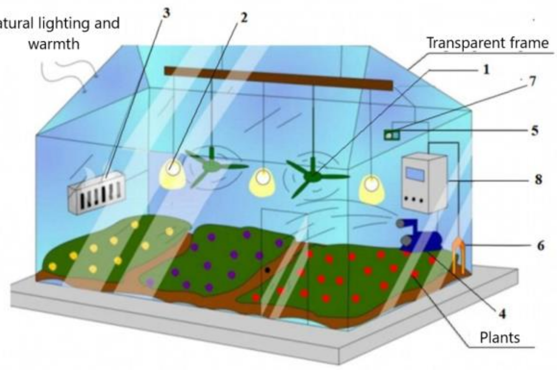

Fig. 2. Graphical representation of the system application: 1 - fans; 2 - lighting lamps; 3 - air conditioner; 4 - water pump; 5 - relative humidity and temperature sensors; 6 - soil moisture sensor; 7 - light level sensor; 8 - control unit

The hardware system consists of three subsystems for microclimate control (see Fig. 2):

I - temperature and relative humidity control;

I - контроль температури та відносної вологості;

III - light level control.

Subsystem I is responsible for real-time monitoring of the humidity and temperature parameters in the greenhouse and ensures that they are maintained within the specified limits. The greenhouse system has certain static levels of humidity and temperature, and when these parameters go beyond the set values, the microcontroller sends a signal to the interface devices (labeled as 8), which activate the air conditioner 3 and fans 1 to restore the required conditions. The ATmega 328 microcontroller receives analog signals (Input) from humidity and temperature sensors 5 and generates digital signals (Output). The algorithms of subsystem I are shown in the block diagram in figure 3.

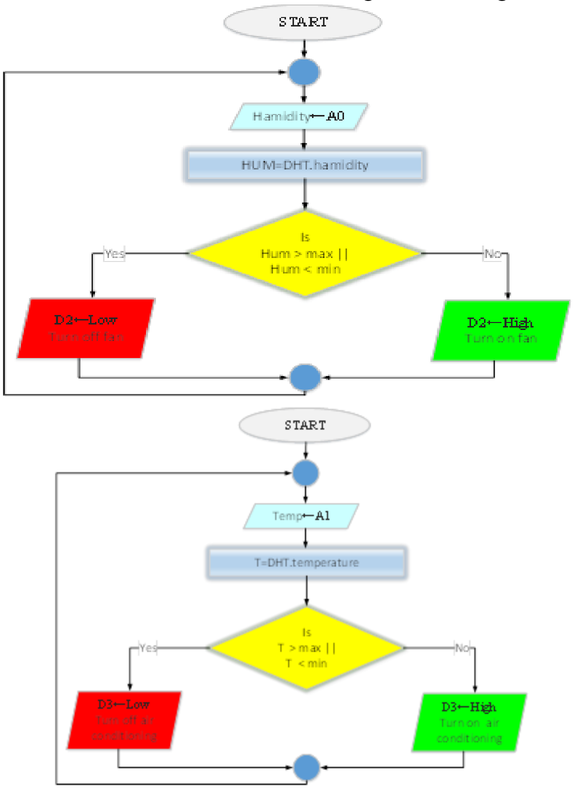

Fig. 3. Algorithms of subsystem I

Subsystem II is responsible for monitoring the soil moisture level in the artificially created ecosystem. If insufficient moisture is detected, sensor 6 (see Fig. 2) generates a signal that is sent to the Arduino UNO located in the control unit 8. The ATmega 328 microcontroller, in turn, sends a command to turn on the irrigation pump. As soon as the soil moisture level reaches the desired value, the microcontroller sends a signal to turn off the pump. The program code loaded into the memory of the Arduino UNO board performs these functions according to the algorithm shown in figure 4.

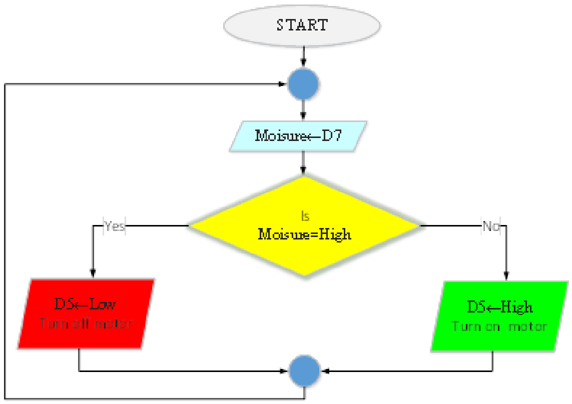

Fig. 4. Algorithm of subsystem II operation

Subsystem III is responsible for monitoring and controlling the light level. If the illumination does not meet the standard values, the sensor 7 (see Fig. 2) sends a signal to the microcontroller, which generates a corresponding signal to the control device to turn on the light. When the level of sunlight reaches the required value, the microcontroller sends a signal to turn off the light. The program for turning the light on or off depending on the intensity of sunlight is loaded into the microcontroller's memory and is executed according to the algorithm shown in figure 5 .

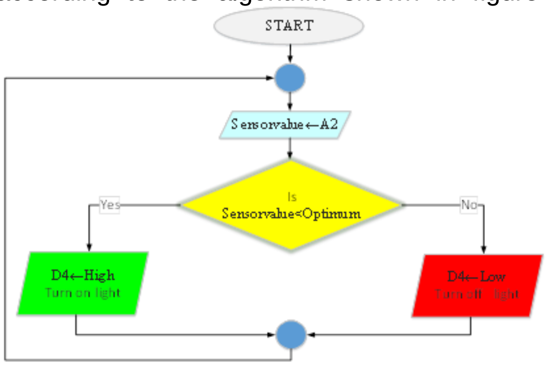

Fig. 5. Algorithm of subsystem III operation

Control of humidity, soil temperature, daylight and CO2 levels can be considered as a secondary monitoring stage. During the daytime, the main regulated parameter is the internal temperature, which is controlled by means of ventilation holes. Natural ventilation provides air exchange between the interior of the greenhouse and the outside environment, which allows the temperature inside to decrease.

To achieve the desired temperature, the controller calculates the optimal vent size. The internal temperature can also be regulated by means of forced ventilation and heaters. Cost-effective wireless sensor nodes such as the Programmable System on Chip (CY3271) from Cypress Inc. can be used to monitor some greenhouse parameters. These kits operate at 2.4 GHz, are easy to use and energy efficient for wireless connections in embedded systems.

The kit includes a PC bridge (FTPC) for programming all PSoC devices in the CY3271 kit. It serves as a concentration point in CyFi wireless networks. The kit includes a multifunctional expansion board (FTMF) with a capacitive sensor, proximity sensor, light sensor, thermistor, and LED cluster. There is also a radio frequency card (FTRF) as a transceiver that can work as a master node in a wireless CyFi system and has a built-in thermistor for temperature measurement.

As for the event management system, it is planned that the greenhouse will be equipped with a wireless sensor network (WSN), where each sensor transmits data only when the difference between the current and previous values exceeds a set threshold. The first step is to determine the appropriate thresholds for each greenhouse parameter. This threshold directly affects the frequency of event generation and the amount of data transmitted. Typical values for some parameters are shown in Table 1.

Table 1: Constraints for greenhouse variables

Variable	Border δ =3%	Border δ =5%
Soil temperature	0.48	0.57
Wind flow	10.70	17.84
Soil moisture	3.0	5.0
Solar radiation	28.58	34.3
Humidity	1.2	2.0
Internal temperature	0.36	0.66
External temperature	0.36	0.61

As shown in Table 1, individual limits for the most common variables are used for control. These limits, δ=3% and δ=5%, were determined based on the available data. The value of δ for each variable is calculated by taking into account the difference of 3% and 5% between the maximum and minimum values. The chosen limits allow us to assess their impact on the system. The wireless sensor network (WSN) monitors events in accordance with the specified limits, and control actions are taken based on the modeling results.

Plant growth is largely dependent on climatic conditions, the amount of water and fertilizer used during irrigation. Greenhouses are ideal for growing plants because they allow you to adjust the climate and fertilizer dosage, providing optimal conditions for plant growth and development.

Since climate conditions and fertilization are separate aspects, different approaches are required to manage them. Automated systems that work on the basis of collected data can determine and regulate the nutrient and water needs of plants. The amount of water and fertilizer required by plants depends on climatic conditions, which makes growing in greenhouses difficult.

Climate parameters in greenhouses are dynamic and are shaped by a combination of physical processes such as energy transfer (including radiation and heat) and mass balance (including water vapor fluxes and CO2 concentration). These processes depend on the environment, greenhouse design, the effectiveness of management mechanisms, and the type of crops grown. The main methods of climate control are ventilation and heating, while artificial lighting is used to regulate temperature, humidity and shading. The introduction of CO2 affects photosynthesis, and humidification helps to control misting.

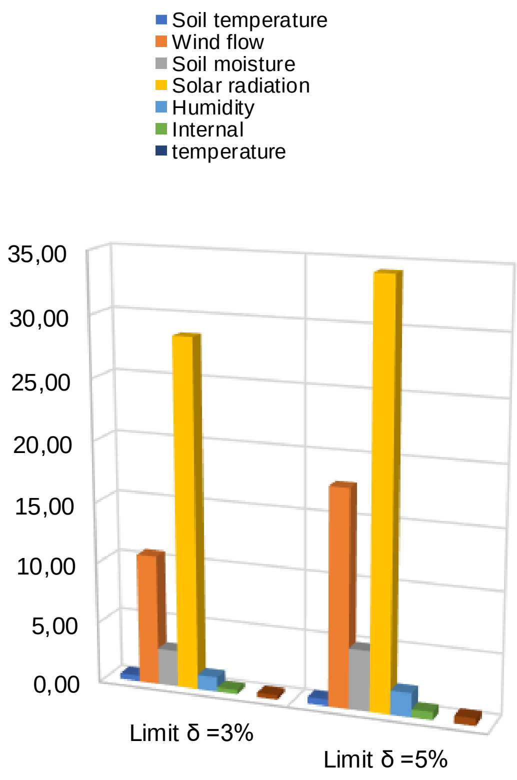

Fig. 6 Limit values of greenhouse parameters

The article proposes a method for controlling climatic conditions in greenhouses during different seasons without CO2 enrichment, taking into account the growing demand for quality products. The main climate parameters to be controlled are temperature and humidity. Photosynthetically active radiation (PAR), which is in the spectral range from 400 to 700 W/m², is used by plants as a source of energy for photosynthesis. PAR is regulated by curtain screens, although their use is not yet widespread.

Sensor node "A", which monitors the external climate conditions, periodically collects data on wind speed and direction, light level, temperature, atmospheric pressure, humidity and CO2 content in the air. Sensor node "B", located inside the greenhouse, monitors internal conditions such as light, temperature, atmospheric pressure, humidity and CO2 content. The "C" node, responsible for monitoring the soil, is specially configured to measure soil moisture, temperature, pH, and electrical conductivity.

The minimum amount of memory required to store data is one byte per parameter, so node "A" requires 7 bytes, node "B" requires 5 bytes, and node "C" requires 4 bytes.

Plant growth is largely dependent on the process of photosynthesis, which is determined by the level of photosynthetically active radiation. It has been found that the right temperature conditions affect the rate of sugar production during photosynthesis. Temperature control is critical, as an increase in radiation levels can lead to an increase in temperature. Therefore, during the day, it is necessary to maintain the optimal temperature for efficient photosynthesis, and at night, when plants are inactive, high temperature levels are not necessary. Thus, two modes of temperature control are considered: day and night [13].

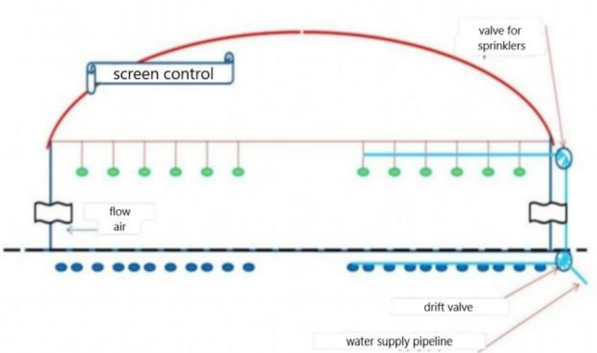

Fig. 7. Controls in the greenhouse

In favorable weather conditions, the daytime temperature reaches the optimum level due to the sun's heat. The main task of daytime temperature control is to cool the greenhouse through natural ventilation to achieve the desired temperature. At the same time, at night, the greenhouse needs to be heated to maintain the required temperature. In such cases, circulation heaters are often used for night heating.

Water vapor in the greenhouse is one of the key variables affecting plant growth. High humidity can promote disease and reduce transpiration, while low humidity can cause water stress, leading to stomatal closure and consequently reduced photosynthesis, which depends on CO2 uptake. Controlling humidity is challenging because temperature and relative humidity change inversely.

Temperature and humidity are controlled by the same mechanisms, with the main priority given to temperature control, as it is a key factor in plant growth. Depending on the current humidity level, the temperature can be adjusted to maintain the humidity in the desired range. Effective humidity control involves the exchange of internal air with external air through the greenhouse ventilation system [14].

The climate in the greenhouse is controlled by an event-based control system, where the sampling method is determined by signal changes. This system only transmits data when there is a significant change in the signal that justifies the need for a new sample. This method is also known as adaptive sampling or the delta change method. A block diagram of a greenhouse climate control system using WSNs is shown in figure 8.

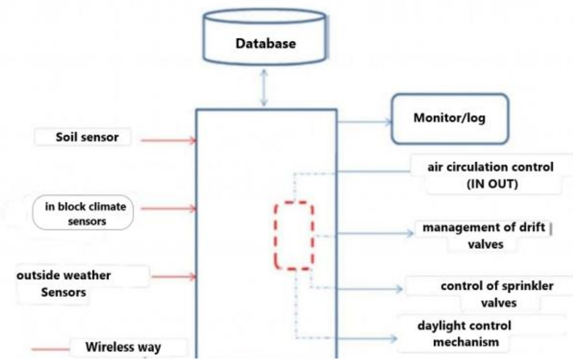

Fig. 8 Diagram of WSN control units for Green House

As can be seen from Fig. 8, an event-based control system consists of two main components: an event detector and a controller. The event detector notifies the controller of the need to calculate a new control signal in response to a new event. In this paper, it is proposed to develop a wireless sensor network (WSN) to manage day and night parameter control using natural ventilation, heating, shielding, and sprinkler irrigation system as the main methods. Humidity, soil temperature, lighting, and CO2 control are considered secondary objectives.

During the day, the main control parameter is the internal temperature, and the corresponding control signal is used to control the vents. Natural ventilation promotes the exchange of air between the indoor and outdoor environment, which helps to reduce the temperature inside the greenhouse. The controller determines the required vent size to achieve the desired temperature level. The internal temperature can also be regulated with forced-air heaters, and the heating system is controlled with on/off controllers with a dead zone function.

For some greenhouse parameters, cost-effective wireless sensor nodes can be created using Programmable Systems on a Chip (CY3271) from Cypress Inc. These low-power RF kits are designed to handle mixed signals and provide high reliability, ease of use, and energy-efficient wireless connectivity for embedded systems. They operate at 2.4 GHz and include a PC Bridge (FTPC) for programming PSoC devices, a Multifunctional Transceiver Board (FTMF) with various sensors and LEDs, and a Radio Frequency Transceiver Card (FTRF) for data transmission.

Conclusions and directions for further research. Thus, the implementation of the proposed greenhouse control system ensures monitoring and automatic adjustment of parameters to specified levels. The response of the subsystems to changes in microclimatic conditions has a delay of several microseconds, determined by the programmed scanning cycle. In addition, this system almost completely eliminates the risk of human error in greenhouse maintenance, as the measurement of light intensity, temperature and humidity is automated.

However, despite their high efficiency and cost-effectiveness, modern automated greenhouse control systems, including the developed system, have a fixed arrangement of components and mostly rigid connections between them. Improving their technological level is usually achieved by using more accurate sensors, modernizing equipment to adjust environmental parameters, and improving data processing algorithms. However, the issue of increasing the flexibility and mobility of the system by increasing its adaptability remains open and requires further research.

Given the diversity of crops grown, which is increasing due to the development of agricultural technologies, more parameters need to be monitored. In such circumstances, a wireless sensor network with complementary hardware and software is an effective solution for greenhouse management.

The hardware from Cypress Inc. has been experimentally proven to be the best option due to its low power consumption, ease of use, and high reliability. However, if the number of parameters continues to grow, the current throughput of WSN technology may become insufficient. In this case, a WSN with cognitive radio may be a viable solution.

This progress in precision agriculture through wireless sensor networks is extremely beneficial, especially for developing countries where agriculture is the main industry.

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ІНТЕГРАЦІЯ СЕНСОРНИХ ТЕХНОЛОГІЙ У СТРУКТУРНУ СХЕМУ АВТОМАТИЗОВАНОГО УПРАВЛІННЯ ТЕПЛИЦЯМИ

Розвиток технологій бездротової сенсорної мережі відкрив нові можливості для моніторингу та контролю параметрів теплиці в точному землеробстві. Значний прогрес у сільськогосподарських технологіях за останні десятиліття сприяв підвищенню врожайності сільськогосподарських культур. В умовах нерівномірного природного розподілу опадів фермерам вкрай важливо стежити за рівномірним розподілом води для всіх культур у господарстві або відповідно до потреб окремих культур. Немає універсального способу зрошення, який би відповідав будь-яким погодним умовам, типам ґрунту та сільськогосподарським культурам.

Тепличні технології можуть запропонувати оптимальне вирішення цієї

проблеми. Вибір правильного методу вимагає детального аналізу всіх параметрів теплиці. Фермери часто зазнають значних фінансових втрат через неточні прогнози погоди та неправильні методи зрошення своїх посівів.

Метою дослідження є створення умов для підвищення ефективності вирощування овочів у теплицях шляхом впровадження високоінтегрованих систем контролю, моніторингу, управління та автоматизації. Це передбачає розробку структурної схеми мехатронної розумної системи моніторингу та управління технологічними процесами.

В результаті проведених досліджень розроблено структурну схему автоматизованого управління теплицею. У цій схемі блок адаптації порівнює отримані значення параметрів середовища з нормативними значеннями. У разі виявлення відхилень система подає інформаційні сигнали для коригування агрокліматичних умов, вмикаючи відповідні виконавчі механізми — зволожувачі повітря, освітлювальні лампи, системи внутрішнього зрошення, опалення.

Ключові слова: *гідропоніка, енергоефективність, продуктивність, штучне освітлення, теплиця, вирощування рослин, рослинність, фотосинтез, живлення.*

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