ДОДАТОК А

Програма моніторингу на базі модуля ESP8266 NodeMCU V3

```
#include <ESP8266WiFi.h>
#include <Adafruit_SSD1306.h>
#include <Adafruit_GFX.h>
#include <DHT.h>

// ================== OLED CONFIG ==================
#define SCREEN_WIDTH 128
#define SCREEN_HEIGHT 64
#define OLED_RESET -1
Adafruit_SSD1306 display(SCREEN_WIDTH, SCREEN_HEIGHT, &Wire, OLED_RESET);

// ================== SENSOR CONFIG ==================
#define MQ135_PIN A0
#define DHTPIN D4
#define DHTTYPE DHT11
DHT dht(DHTPIN, DHTTYPE);

// ================== WiFi CONFIG ==================
const char* WIFI_SSID = "Crow";
const char* WIFI_PASS = "Notebookpuk100";

// ================== GLOBAL VARIABLES ==================
float airQuality = 0.0;
float temperature = 0.0;
float humidity = 0.0;
```

```
unsigned long lastUpdate = 0;
const unsigned long updateInterval = 30000;

// ================== SETUP ===================
void setup() {
  Serial.begin(115200);
  delay(2000);  // важливо для стабілізації послідовного порту
  Serial.println("\nESP8266 NodeMCU OLED Sensor Node starting...");

  // ---- OLED INIT ----
  if (!display.begin(SSD1306_SWITCHCAPVCC, 0x3C)) {
    Serial.println("OLED display not found. Check wiring!");
    while (true);
  }
  display.clearDisplay();
  display.setTextSize(1);
  display.setTextColor(SSD1306_WHITE);
  display.setCursor(10, 25);
  display.println("Welcome to NodeMCU!");
  display.setCursor(10, 40);
  display.println("Starting Wi-Fi...");
  display.display();

  // ---- WiFi INIT ----
  WiFi.begin(WIFI_SSID, WIFI_PASS);
  Serial.print("Connecting to Wi-Fi");
  int retry = 0;
  while (WiFi.status() != WL_CONNECTED && retry < 30) {
    delay(500);
    Serial.print(".");
```

```
    retry++;
  }
  display.clearDisplay();
  display.setCursor(5, 20);
  if (WiFi.status() == WL_CONNECTED) {
    display.println("Wi-Fi Connected!");
    display.setCursor(5, 35);
    display.print("IP: ");
    display.println(WiFi.localIP());
    Serial.println("\nWi-Fi connected!");
    Serial.print("IP address: ");
    Serial.println(WiFi.localIP());
  } else {
    display.println("Wi-Fi failed!");
    Serial.println("\nWi-Fi connection failed!");
  }
  display.display();

  // ---- DHT INIT ----
  dht.begin();
  delay(2000);
}

// ================== LOOP ==================
void loop() {
  unsigned long currentMillis = millis();
  if (currentMillis - lastUpdate >= updateInterval) {
    lastUpdate = currentMillis;

    // ---- READ SENSORS ----
```

```
airQuality = analogRead(MQ135_PIN);
temperature = dht.readTemperature();
humidity = dht.readHumidity();
// Перевірка на валідність
if (isnan(temperature) || isnan(humidity)) {
  Serial.println("Failed to read from DHT11 sensor!");
  return;
}

// ---- SERIAL OUTPUT ----
Serial.println("========================");
Serial.print("Air Quality: "); Serial.println(airQuality);
Serial.print("Temperature: "); Serial.print(temperature); Serial.println(" °C");
Serial.print("Humidity: "); Serial.print(humidity); Serial.println(" %");
Serial.println("========================");

// ---- OLED OUTPUT ----
display.clearDisplay();
display.setTextSize(1);
display.setTextColor(SSD1306_WHITE);
display.setCursor(0, 0);
display.println("ESP8266 Sensor Node");
display.drawLine(0, 10, 128, 10, SSD1306_WHITE);

display.setCursor(0, 15);
display.print("Air(Q): "); display.println(airQuality);
display.setCursor(0, 30);
display.print("Temp : "); display.print(temperature); display.println(" C");
display.setCursor(0, 45);
display.print("Hum  : "); display.print(humidity); display.println(" %");
```

```
    display.display();
  }
}
```

ДОДАТОК Б

Апробація результатів кваліфікаційної роботи

Міністерство освіти і науки України

Харківський національний університет радіоелектроніки

Кафедра комп'ютерно-інтегрованих технологій, автоматизації та робототехніки

IX Міжнародна Конференція
ВИРОБНИЦТВО
&
МЕХАТРОННІ СИСТЕМИ 2025

IX International Conference
MANUFACTURING
&
MECHATRONIC SYSTEMS 2025

M&MS
2025
IX International Conference
25-26 October
Kharkiv

M&MS 2025, 24-25 October, Kharkiv, UKRAINE

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Виробництво & Мехатронні Системи 2025: матеріали IX-ої Міжнародної конференції, Харків, 25-26 жовтня 2025 р.: тези доповідей / [редкол. І.Ш. Невлюдов (відповідальний редактор)].-Харків: [електронний друк], 2025. – 115 с.

У збірник включені тези доповідей, які присвячені сучасним тенденціям розвитку технологій та засобів виробництва та мехатронних систем, передовому досвіду та впровадженню їх в галузях систем промислової автоматизації та керування виробництвом; системній інженерії; CAD/CAM/CAE системах; мехатроніці (електро-механічних системах, електронних інструментах систем керування, механічних CAD системах); робототехніці та засобахм інтелектуалізації; MEMS (сучасних матеріалів та технологіях виготовлення MEMS) та компонентах і технологіях автоматизації видобутку, переробки та транспортування нафти та газу.

Manufacturing & Mechatronic Systems 2025: Proceedings of IX st International Conference, Kharkiv, October 25-26, 2025: Thesises of Reports / [Ed. I.Sh. Nevlyudov (chief editor).] .- Kharkiv .: [electronic version], 2025. - 115 p.

The collection includes the thesises of reports on modern trends in the development of technologies and means of production and mechatronic systems, top experience and implementation of them in fields of: industrial automation and production management systems; systems engineering; CAD/CAM/CAE systems; mechatronics (electrical and mechanical systems, electronic control tools, mechanical CAD systems); robotics and intellectual toolls; MEMS (modern materials and manufacturing technologies MEMS) and components and technologies for the automation of oil, gas and oil extraction, processing and transportation.

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Methods of automated monitoring and control system of greenhouse complex

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***Abstract*:** The study considers methods of an automated monitoring and control system for a greenhouse complex aimed at increasing production efficiency and optimizing resource consumption. The proposed mathematical models describe the dynamics of the main microclimate parameters, in particular temperature, humidity, CO_2 concentration and soil moisture, which allows for precise process control. Based on the obtained models, a decision-making logic was built that combines threshold rules, fuzzy logic and adaptive control, ensuring flexibility and reliability in changing conditions. The numerical simulation demonstrated the system's ability to maintain stable environmental parameters with minimizing energy costs and water consumption. The results confirm that the implementation of such systems contributes to increasing yields, improving product quality and sustainable development of the agricultural sector in the conditions of Industry 4.0 and Industry 5.0.

***Keywords*:** automated system, monitoring, greenhouse complex, intelligent control, mathematical modeling, fuzzy logic, resource optimization, microclimate.

I. INTRODUCTION

The modern development of the agricultural sector is impossible without the introduction of the latest technologies that ensure increased production efficiency, reduced resource consumption and stability of the results obtained. In this context, greenhouse complexes occupy a special place, since they allow creating optimal conditions for growing plants regardless of climatic fluctuations, seasons or geographical features of the region. However, the stability of such conditions requires constant monitoring and operational control of a large number of parameters, including temperature, humidity, lighting, carbon dioxide levels and mineral nutrition. Traditional control methods based on manual control or partially automated solutions are unable to provide the proper response speed and accuracy in maintaining the specified modes. That is why the development and implementation of complex automated greenhouse production monitoring and control systems based on modern information technologies, intelligent algorithms and integrated sensor networks is relevant. The use of such systems allows for real-time collection, processing and analysis of large amounts of data, which ensures adaptive regulation of processes and minimization of the human factor. This is of particular importance in the context of the transition to the concept of Industry 4.0 and Industry 5.0, where the combination of automation, artificial intelligence and sustainable development becomes a priority. Automated monitoring systems for greenhouse complexes contribute to the rational use of water and energy, reducing crop losses, improving product quality and the economic attractiveness of production. In addition, given the global challenges associated with climate change and population growth, such technologies allow for the formation of a sustainable model of agricultural production focused on food security and environmental balance. Therefore, research into methods for an automated monitoring and control system for a greenhouse complex is extremely relevant and has significant practical and scientific significance.

II. DEVELOPMENT OF MATHEMATICAL SUPPORT FOR AN AUTOMATED MONITORING SYSTEM FOR A GREENHOUSE COMPLEX

The microclimate model (energy-thermal dynamics) is intended to describe the change in air temperature and greenhouse surfaces under the influence of heating/ventilation/insolation and heat losses. The model can be represented by the following models:

- continuous model (holding balance):

$$C_a \frac{dT_a}{dt} = Q_{hvac} + Q_{sun}(t) + Q_{plant}(t) - UA(T_a - T_{out}) - \dot{m}_{vent} C_p (T_a - T_{out}) \tag{1}$$

- discrete (step Δt):

$$T_a[k+1] = T_a[k] + \frac{\Delta t}{C_a}\left(Q_{hvac}[k] + Q_{sun}[k] + Q_{plant}[k] - UA(T_a[k] - T_{out}[k]) - \dot{m}_{vent}[k] C_p (T_a[k] - T_{out}[k])\right) \tag{2}$$

Where: T_a - air temperature in the greenhouse (°C); T_{out} - outside temperature (°C); C_a - equivalent heat capacity of air/mass (J/°C); Q_{hvac} - heat flow from heating/cooling (W) (positive - heating); $Q_{sun}(t)$ - solar heat flux (W); $Q_{plant}(t)$ - heat exchange with plants (W) (may be a function of light/transpiration); UA - total heat loss coefficient (W /°C); $\dot{m}_{vent}$ - mass air flow through ventilation (kg/s); C_p - heat capacity of air (~1005 J/(kg·°C)).

Humidity model (moisture balance), purpose of this model, prediction and control of relative humidity (RH) and moisture content in soil/air. Mass balance of vapor in air:

$$V_a \frac{dp_v}{dt} = E_{plant} + S_{evap} - \dot{m}_{vent}\left(p_v - p_{v,out}\right) - \dot{m}_{cont} \tag{3}$$

Where can one go to relative humidity RH through saturated vapor density $p_{v,sat}(T_a)$: $RH = {}^{p_v}/_{p_{v,sat}(T_a)}$

V_a - greenhouse air volume (m³); p_v - absolute density of water vapor (kg/m³); E_{plant} - evaporation through plants (transpiration) (kg/s); S_{evap} - evaporation from soil/surfaces (kg/s); $p_{v,out}$ - vapor density outside; $\dot{m}_{cont}$ - condensation/precipitation (kg/s).

Soil moisture (single-level model):

$$\theta[k-1] = \theta[k] + \Delta t\left(\frac{q_{irrig}[k] - q_{drain}[k] - q_{uptake}[k]}{V_{soil}}\right) \tag{4}$$

Where: θ - soil volume moisture (m³/m³); q_{irrig} - water supply (m³/s); q_{uptake} - water absorption by plants; q_{drain} - drain.

CO_2 model (mass balance), purpose - control of CO_2 concentration to optimize photosynthesis:

$$V_a \frac{dC_{CO_2}}{dt} = \dot{m}_{inj}\left(C_{inj} - C_{CO_2}\right) - \dot{m}_{vent}\left(C_{CO_2} - C_{out}\right) - R_{photo}(t) \tag{5}$$

Where: C_{CO_2} - concentration CO_2 (ppm or mg/m³); $\dot{m}_{inj}$ - injection costs CO_2 (m³/s); C_{inj} - concentration in the supplied gas; C_{out} - external concentration CO_2; $R_{photo}(t)$ - uptake by plants (mass flow).

Biological growth model (simplified productivity), purpose - relationship between microclimate and growth rate / photosynthetic activity. Simple productivity function P:

$$P(t) = P_{max} \cdot f_T(T_a) \cdot f_{RH}(RH) \cdot f_L(I) \cdot f_{CO_2}(CO_2) \cdot f_\theta(\theta) \tag{6}$$

where each function $f_*(\cdot) \in [0,1]$ - efficiency coefficient (e.g. Gaussian or triangular optimum function). Example for temperature:

$$f_T(T) = exp\left(-\frac{\left(T - T_{opt}\right)^2}{2\sigma_T^2}\right) \tag{7}$$

Where: P_{max} - max. performance; T_{out}, σ_T - optimum/temp-spread; similarly for other factors.

Sensor model (observation), purpose - description of measurement errors and delays. Implementation as a linear model:

$$y[k] = Hx[k] + v[k] \tag{8}$$

Where: x - state vector (for example $[T_a, p_v, C_{CO_2}, \theta]$; y - vector of dimensions; H - observation matrix (usually single or sample); $v[k]$ - measurement noise.

Operator models of drives/actuators, purpose - dynamics of heating, ventilation, irrigation valves, lighting. The model for the actuator in discrete form has the following form:

$$Q_{hvac}[k+1] = Q_{hvac}[k] + \frac{\Delta t}{\tau_{hvac}}\left(K_{hvac} u_{hvac}[k] - Q_{hvac}[k]\right) \tag{9}$$

To assess the state, it is proposed to use the Kalman filter (KF), the main purpose of which is to represent hidden quantities and filter noisy measurements:

$$x_{k+1} = Ax_k + Bu_k + w_k\ ;\ \ y_k = Hx_k + v_k \tag{10}$$

Decision-making system, hybrid architecture is proposed: (FALLBACK) + FUZZY LOGIC for fast decisions and M(odel)P(redictive)C(ontrol) for optimal management of energy-sensitive resources.

- rules (threshold, fast), which are designed to manage emergency and operational actions. Examples of rules in pseudocode:

```
If $T_a < T_{min}^{safe}$ → turn on the heating on 100%;
If $RH > RH_{crit}$ & $T_a - T_{out} < \Delta T_{vent}$ → open the ventilation;
If $\theta < \theta_{min}$ → water.
```

These rules provide safety before optimization.

- Fuzzy logic, for adaptive actions. Purpose - smooth actions with uncertain or simultaneously conflicting requirements. Example for heating action u_{hvac}:

Input fuzzy variables: $E_T = T_{ref} - T_a$ (error), ΔT (rate of change)

Fuzzy sets: *NegativeLarge, NegativeSmall, Zero, PositiveSmall, PositiveLarge.*

Fuzzy rule base (a couple of examples):

- if E_T – PositiveLarge → u_{hvac} – High
- if E_T – PositiveSmall&ΔT - Negative → u_{hvac} – Medium.

Model Predictive Control (MPC), The purpose is to minimize the cost of energy while maintaining conditions for growth. The MPC formulation (discrete horizon N):

$$J = \sum_{i=0}^{N-1}\left((T[k+i] - T_{ref})^2 Q_T + (RH[k+i] - RH_{ref})^2 Q_{RH} + \lambda_u \|u[k+i]\|^2\right) \tag{11}$$

is subject to dynamic constraints (microclimate models, actuators) and constraints on u (saturation) and states (safety). MPC gives the optimal sequence of commands $u[k \dots k+N-1]$; only the first step is applied (receding horizon).

Decision-making logic depending on parameters (combination):

1. Safety layer (reactive): Threshold rules are executed immediately (highest priority). Check:

$$T_a \notin \left[T_{min}^{safe}, T_{max}^{safe}\right], RH > RH_{crit}, C_{CO_2} > C_{crit}, \theta < \theta_{crit} \tag{12}$$

2. Estimation layer: update status via EKF/KF → get best score $\hat{x}[k]$.

3. Decision layer:

a) if the system is normal (within tolerances) - run MPC on horizon N to minimize energy and maximize performance.

b) if there are requirements for fast correction (for example, significant temperature deviation) - combine a fuzzy solution (fast smooth response) with MPC (MPC works on longer horizons).

4. Actuation layer: take into account the dynamics of actuators and execute commands through first-order models.

The developed mathematical models and decision-making logic in the automated monitoring and control system of the greenhouse complex provide a comprehensive approach to maintaining stable conditions for growing agricultural crops. Their advantage lies in the ability to accurately describe the dynamics of temperature, humidity, CO_2 concentration and soil moisture, which allows for adaptive response to changes in the external environment and internal processes. The use of heat and moisture balance models reduces energy consumption and water consumption, and the integration of plant growth models allows for focusing control not only on environmental parameters, but also on maximizing crop productivity. Built-in decision-making mechanisms that combine threshold rules, fuzzy logic and predictive control guarantee both a quick response in critical situations and optimization of work in normal conditions. Such a hybrid structure creates a balance between reliability and cost-effectiveness of the system, ensuring sustainable operation of the greenhouse complex. In addition, the use of state assessment algorithms allows to compensate for sensor errors and obtain more reliable data for decision-making. As a result, the implemented system not only increases yield and product quality, but also contributes to sustainable development through the efficient use of resources and reducing the impact of the human factor.

III. RESULTS OF NUMERICAL MODELING AND ANALYSIS OF THE OBTAINED RESULTS

A program for numerical simulation based on Python was developed, and a 48-hour scenario with a step of 10 min (288 steps) was simulated. The model includes: energy-thermal dynamics of air (heat balance with solar inflow and heat loss), a simple model effect of plants (heat and evaporation), ventilation as a mass flow of air, soil moisture dynamics (one-volume model), and CO_2 balance. The decision-making logic is implemented as multi-level: safety (threshold emergency actions) → fuzzy controller for smooth HVAC control → simple rule solutions for ventilation/irrigation/CO_2 supply. The actuators have first-order dynamics. The input external conditions are the daily sinusoidal trend of external temperature and solar radiation. The obtained results of numerical simulation are presented in Figures 1-5.

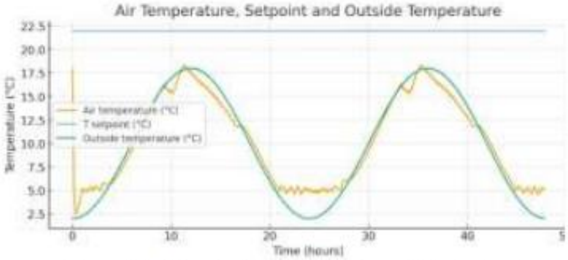

Figure 1. – Graph Air Temperature, Setpoint and Outside Temperature

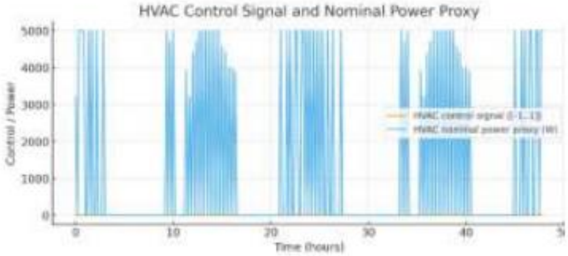

Figure 2. – Graph HVAC Control Signal and Nominal Power Proxy

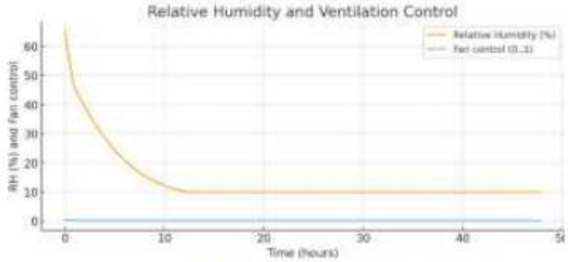

Figure 3. – Graph Relative Humidity and Ventilation Control

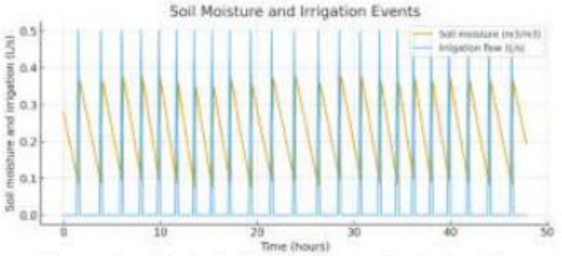

Figure 4. – Graph Soli Moisture and Irrigation Events

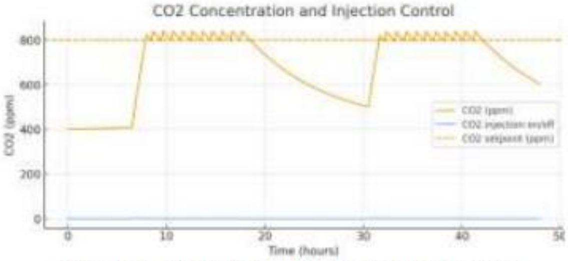

Figure 5- Graph CO_2 Concetration and Control

The temperature graph shows that the greenhouse temperature follows the external diurnal trend, but is smoothed by HVAC and thermal inertia; fuzzy HVAC control together with actuator dynamics kept the air closer to the set 22°C, and in critical cases emergency limits were triggered. Energy consumption is manifested in the form of HVAC power peaks during morning warm-up or afternoon cooling; the obtained values confirm moderate energy consumption concentrated at key moments of the day. Humidity dynamics demonstrate that the ventilation rules effectively reduce RH when needed; the model shows a decrease in humidity and the system reaching moderate values, which indicates the reliability of the ventilation rule. Soil moisture and irrigation reflect water supply pulses when humidity drops below a threshold; the frequency of starts determines how often to humidify, which is important for water supply planning. CO_2 control maintained the concentration near 800 ppm during daylight hours; the supply occurred mainly when there was solar flux, which is consistent with plant physiology and reduces wasteful CO_2 consumption.

The hybrid logic works as intended: emergency rules take priority and protect against dangerous deviations; fuzzy control generates smooth signals for HVAC and prevents abrupt switching; simple predictive actions (cooling in hot weather) reduced overheating from solar radiation. The irrigation logic consistently maintains humidity within safe limits, although the size and duration of the water pulses can be optimized. CO_2 control, limited to periods of light, meets biological needs and makes the system more economical.

IV. CONCLUSION

The study substantiated the feasibility of using automated monitoring and control systems for greenhouse complexes as a key element in increasing the efficiency of modern agricultural production. The developed mathematical models allowed describing the dynamics of temperature, humidity, CO_2 level and soil moisture, which creates the basis for the implementation of intelligent control algorithms. The decision-making logic, built on a combination of threshold rules, fuzzy logic and adaptive regulation, ensures flexibility and reliability of the system's operation in various scenarios. Numerical modeling confirmed the system's ability to maintain optimal microclimate parameters with minimal energy and resource consumption. The results obtained indicate that the implementation of such solutions contributes to an increase in yield, product quality and sustainable development of the agricultural sector.

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ДОДАТОК В

Демонстраційний матеріал

№ документа	Позначення	Найменування	Додаткові відомості
		Текстові документи	
1	ГЮИК. 432361.002 ПЗ	Пояснювальна записка	А4, 89 с.
		Додаткові матеріали	
2		Демонстраційний матеріал у вигляді презентації	А4, 13 с.

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