exeley INTERNATIONAL JOURNAL ON SMART SENSING AND INTELLIGENT SYSTEMS
Article | DOI: 10.21307/ijssis-2018-017 Issue 0 | Vol. 0

Results of Simulation and Physical Modeling of the Computerized Monitoring and Control System for Greenhouse Microclimate Parameters

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This article was edited by Wanqing Wu.

Received for publication January 15, 2018.

Abstract

The article focuses on the research results concerning development and laboratory testing of simulation and physical models of the computerized monitoring and control system for industrial greenhouse microclimate parameters. The simulation model of the system has been developed and tested in the environment of Proteus computer-aided design. The hardware component has been substantiated and implemented, and the software of the system physical model has been developed by using modern microprocessor and sensor technologies. The priority research of the developed computerized system is identified in order to increase the productivity of industrial greenhouse complexes.

Keywords

Simulation model, Greenhouse, Microclimate, Physical model, Monitoring, System.

Currently, one of the most important and knowledge-intensive forms of modern agriculture is protected horticulture. The main direction of industrial greenhouses modernization is the introduction of adaptive sensory, computerized and infocommunication technologies for monitoring and controlling greenhouse microclimate parameters (Chaudhary et al., 2011; Rehman et al., 2014; Zhang et al., 2015), which contributes to the optimal conditions for growing crops, taking into account their types and vegetation periods. Recently, researchers in the field of information and measurement systems have begun to pay increased attention to the development and implementation of intelligent adaptive microprocessor systems for monitoring and control process parameters in agricultural facilities. This enables the technological and economic component of the protected horticulture process to increase.

On-line monitoring of air temperature and humidity in the cultivation area, soil temperature and moisture in the root area, temperature and acidity of the solution during irrigation, effective illumination of the cultivation area in the visible optical range, taking into account the daily dynamics of natural light, carbon dioxide concentration and air velocity in the cultivation area allow agronomists to analyze the integral influence of the above factors on crop growth regimes. Requirements to the quality of agricultural products are dynamically increasing which determine the relevance of continuous research on the improvement of computerized devices for monitoring and controlling the technological processes of growing vegetables in greenhouses.

One of the up-to-date and effective tools for conducting research in this field is the methodology of simulation modeling. This approach allows us to conduct a full cycle of research on the development, design and creation of microprocessor monitoring and control systems for the microclimate parameters of greenhouses of various complexity levels. Thus, the development and study of the simulation model of the computerized monitoring and control system for the greenhouse microclimate is an urgent scientific and applied task, the solution of which will enable us to develop a scientific approach to the justification of agrotechnical methods for increasing the rates, volumes, and quality of agricultural greenhouse production.

This paper focuses on the solution of the following applied problem: the limitation of the existing research results concerning effectiveness of computerized monitoring and control of the protected vegetable cultivation technological processes involving simulation modeling methods by means of up-to-date hardware and software.

The purpose of the paper is to substantiate scientific and practical approaches to the development and research of hardware and software tools for computerized monitoring and control of industrial greenhouse microclimate parameters, which will allow us to optimize the technical and economic characteristics of the projected system followed by its subsequent implementation in real operating conditions to increase the rates, volumes, and quality of cultivated greenhouse crops.

The main tasks are as follows:

- to implement a full cycle of simulation and physical modeling of the computerized monitoring and control system for the industrial greenhouse microclimate parameters by applying modern and affordable (low cost) software, sensor, and microprocessor technologies; and
- to substantiate scientific and practical ideas on the structural and algorithmic organization and implementation of the microprocessor system for monitoring and controlling the main regulated parameters of technological processes for growing crops in industrial greenhouses.

The object of the research is the process of computerized monitoring and controlling the regimes of protected vegetable cultivation in on-line mode.

The subject of the research is methods, tools, and techniques for simulation modeling of microprocessor monitoring and control systems for technological processes for the greenhouse production.

The characteristic features of the research results presented in the paper are the use of mathematical and simulation modeling methods of multi-channel measuring and control microprocessor system using modern infocommunication and computerized facilities in order to optimize the structural and algorithmic organization of the computerized measuring system. Verification of the proposed models, methods, and tools adequacy was carried out by testing the developed physical model in laboratory conditions with subsequent obtained results analysis.

The scientific novelty of the results obtained in the paper is the improvement and further development of:

- models for the integral physicochemical state estimating the industrial greenhouses' microclimate, which are based on integral criteria of the complex measurement information processing from space-allocated measuring channels and control units; and
- the structural and algorithmic organization of the computerized remote monitoring and control system for the greenhouses' microclimate parameters, which unlike existing ones, is based on adaptive algorithms to the types and periods of growing crops.

In this paper, the simulation and physical models of the computerized monitoring and control system have been developed for greenhouse conditions. The obtained results are confirmed by testing of the system software implementation and experimental tests of the physical model. Section "Current research findings" explains the current research findings, Section "Materials and methods" explains the materials and methods, Section "Findings" explains all findings, Section "Discussion and conclusions" explains discussion and conclusions from the present work and suggestions for future investigations.

Current research findings

The results of the research presented in this paper are devoted to the development and implementation of the structural and algorithmic organization of the simulation model of a computerized monitoring and control system for the microclimate parameters of industrial greenhouses. The analysis of a priori information on the main approaches to the synthesis and development of hardware and software of modern monitoring and controlling systems of technological regimes of protected cultivation (Kolapkar et al., 2014; Arif and Abbas, 2015; Hwang and Yoe, 2016; Shirsath et al., 2017; Zade et al., 2017) has made it possible to establish their common disadvantages:

- the limited results of the regression analysis of the conversion characteristics of the measuring channels of the greenhouse microclimate physicochemical parameters, namely, temperature (T_{air}) and air humidity (W_{air}) in the cultivation area, temperature (T_{soil}) and soil moisture (W_{soil}) in the root layer, the solution temperature ($T_{solution}$) during irrigation, effective illumination of the cultivation area (E_{area}) in the visible optical range,

Table 1. Proposed methods for disadvantages eliminating.

Research phase	Used approaches and their characteristics
Regression analysis of the sensor conversion characteristics	Based on MS Excel and Mathcad. It allowed to obtain analytical dependencies of the measured parameters, which are the basis for program code
Prototyping of the system	Based on the Fritzing software product. It allowed to increase ergonomic indicators of research results
Simulation modeling of the microprocessor system	Based on Proteus 8.0 (hardware component) and Arduino IDE (software component). It allowed to test the developed structural and algorithmic organization of the system
Analysis of research results	This stage was carried out by comparing of the simulation results and laboratory tests

taking into account the daily dynamics of natural light, carbon dioxide concentration in the cultivation area (C_{co_2}), solution acidity ($pH_{solution}$) during irrigation, air velocity in the crop cultivation area (V_{air});

- the lack of mathematical support for the procedures of complex measurement control of the necessary list of physicochemical parameters of the greenhouse microclimate with regulated metrological characteristics, taking into account the types of crops grown and the periods of their vegetation;
- insufficiency of the research results regarding technologies for remote control of the integral effect of microclimate parameters on greenhouse crops yield indicators with the possibility to predict the dynamics of changes in physical and chemical parameters by using modern technologies; and
- designing systems using an expensive component base, which causes a long payback period for these systems and limits their investment attractiveness (Intelligent Agricultural Solutions, 2017; May Celik, 2017).

Based on the analysis of existing research results of similar systems (Ko and Mon, 2012; Wang et al., 2015; Mhammed and Hussein, 2017; Shabani et al., 2017), the following disadvantages have been established:

- procedure of the measuring channels' models implementing of the recommended parameters' full list is absent;
- the functions of the growing crops modes control do not take into account their types and periods of vegetation; and
- the existing results do not comply with the conditions of complex simulation.

The proposed methods for eliminating established disadvantages are presented in Table 1.

Moreover, having analyzed the existing approaches to the implementation of remote monitoring systems for various processes and phenomena by means of modern technologies, we are able to identify the following fundamentals for the construction of modern systems for remote monitoring of microclimate parameters:

- synthesis of the structural and algorithmic organization of a computerized system, taking into account a complete list of the physical and chemical factors of the greenhouse microclimate (Laktionov et al., 2017a, 2017b);
- implementation of the system development and research stages using up-to-date software for simulation of microprocessor devices (Benrejeb and Boubaker, 2012; Das et al., 2015; Gori Ayub, 2016; Nkenyereye and Jang, 2016) and the main ideas of Internet of Things, Industry 4.0 and Data Mining technologies (Doknić, 2014; Mukhopadhyay and Suryadevara, 2014; Ghayvat et al., 2015; Pirbhulal et al., 2017); and
- implementation of the physical model of the computerized monitoring and control system by means of available and efficient microprocessor platforms (Das et al., 2015; Thati et al., 2015; Dhanalakshmi and Leni, 2017; Laktionov et al., 2017b) and sensor technologies (Mukhopadhyay et al., 2006, 2008; Mohd Syaifudin et al., 2009; Haefke et al., 2011; Laktionov et al., 2017a).

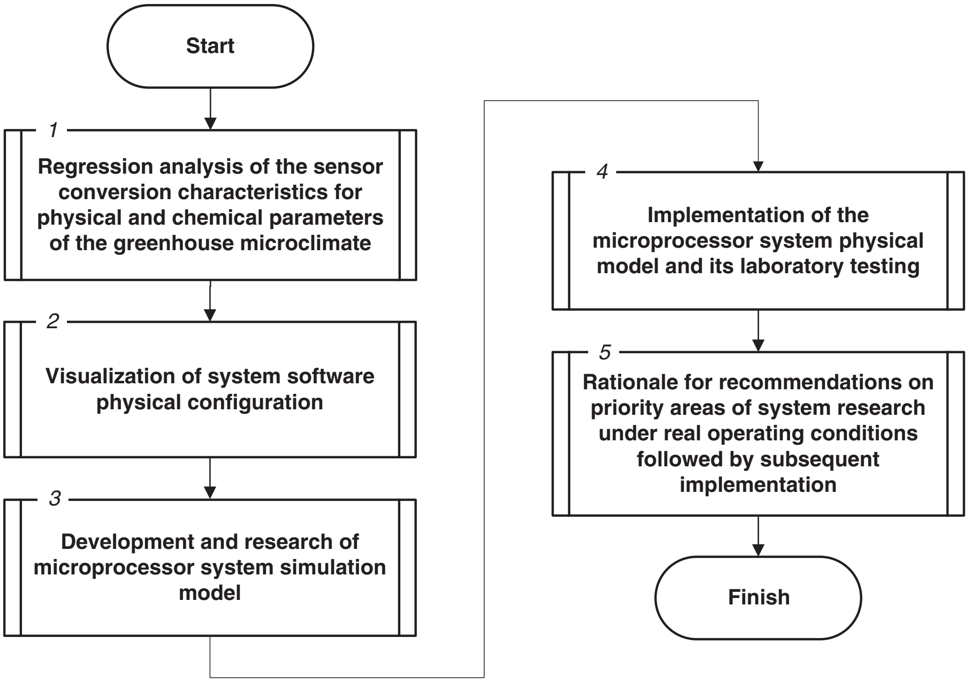

Figure 1: Stages of development and research of the computerized monitoring and control system for the industrial greenhouse microclimate parameters.

Thus, studies on the elimination of these deficiencies in existing systems for computerized monitoring and control of industrial greenhouse microclimate parameters, taking into account the main conceptual ideas for constructing such systems, can be performed by simulation methods. This approach will allow us to synthesize the structural and algorithmic organization of the system and develop recommendations for its implementation in view of all major design stages and full-scale implementation of the microclimate meter suitable for studying various functional features of the system at low economic and labor costs and time expenditure.

Materials and methods

As a basic method for developing the simulation model of the computerized monitoring and control system for the industrial greenhouse microclimate parameters, the method of decomposing the research problem into subtasks has been adopted, as shown in Figure 1.

The main structural and functional components of the simulation model of the computerized monitoring and control system under research are measuring channels of the above-stated physical and chemical parameters of the greenhouse microclimate, the Arduino Mega 2560 microprocessor platform for collecting and processing measurement information, the relay box for synchronizing the microcontroller and the power load, based on LM044L LCD type, as well as specialized software for monitoring and controlling the greenhouse microclimate. This set of components meets the conditions of necessity and sufficiency of the hardware and software development of the microprocessor system in question.

Measuring channel of effective illumination of the cultivation area (E_{area})

The measuring channel (MCh) is based on a photoresistor of the VT83N1 type (VT83N1 Datasheet, 2017), which refers to sensors of the parametric type and is included in the voltage divider circuit, as shown in the microprocessor system diagrams in Figures 8,9. This sensor allows measuring in the range from 10 to 10^4 lux with a total relative error of not more than ±10%, which meets requirements described above (Laktionov et al., 2017a, 2017b). The graphical form of the conversion characteristics obtained on the basis of laboratory tests of the sensor is shown on a logarithmic scale in Figure 2.

The empirical formula shown below is obtained by regression analysis. It describes the characteristics (see Figure 2) with the coefficient of determination $R^2 = 0.944$:

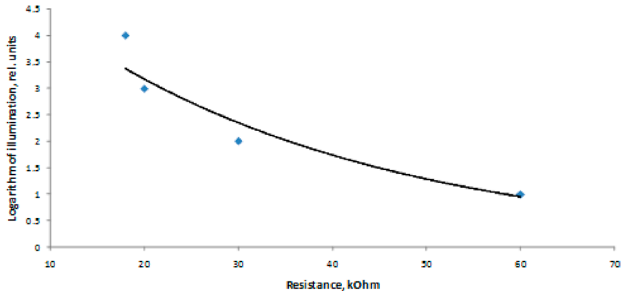

Figure 2: Sensor conversion characteristics for effective illumination of the greenhouse cultivation area.

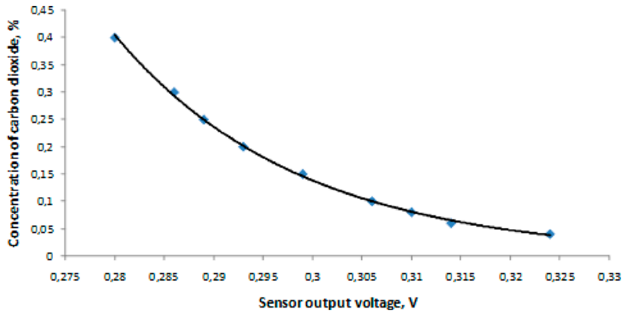

Figure 3: Characteristics of the carbon dioxide concentration sensor conversion.

$$E_{area} = 10^{5.803 \cdot \exp(-0.03 \cdot R_E)}, \quad (1)$$

where E_{area} – effective illumination of the cultivation area, lux; R_E – photoconductive resistance, Ohm.

Measuring channel of carbon dioxide concentration in the cultivation area (C_{co_2})

The MCh in question is implemented on the basis of an electrochemical sensor of the MG811 type (MG811, 2017), which allows measuring in the range from 0.05 to 0.4% with a total relative error of not more than ±5%, which meets the requirements (Laktionov et al., 2017a, 2017b). The prototype connection scheme and the equivalent circuit diagram for connecting the sensor are shown in Figures 8, 9, respectively. The graphical view of the MG811 sensor conversion characteristics obtained from the results of laboratory tests is shown in Figure 3.

The empirical formula shown below is obtained by regression analysis. It describes the characteristics (see Fig. 3), with the coefficient of determination $R^2 = 0.997$:

$$C_{CO_2} = 10^6 \cdot \exp(-53.8 \cdot U_{CO_2}), \quad (2)$$

where C_{CO_2} – carbon dioxide concentration in the cultivation area, %; U_{CO_2} – output voltage of the carbon dioxide concentration sensor, V.

Measuring channel of the solution acidity during irrigation ($pH_{solution}$)

The MCh is implemented on the basis of the ion-selective sensor of the E-201 type (PH meter SKU: SEN0161, 2017), which allows measuring in the range from 0 to 14 units with a total absolute error of not more than ±0.2 units, which meets the requirements stated above (Laktionov et al., 2017a, 2017b). The connection scheme of the prototype model and the equivalent circuit diagram for connecting the sensor are shown in Figures 8,9, respectively. The graphical view of the acidity sensor conversion characteristics obtained on the basis of laboratory tests is shown in Figure 4.

The empirical formula shown below is obtained by regression analysis. It describes the characteristics (see Fig. 4), with the coefficient of determination $R^2 = 0.992$:

$$pH = -17.24 \cdot U_{pH} + 7, \quad (3)$$

where pH – solution acidity during irrigation, ea.; U_{pH} – output voltage of the sensor, V.

Measuring channels of air temperature (T_{air}) and humidity (W_{air})

These measuring channels are built on the basis of the DHT22 sensor type (Gaddam et al., 2014; Aosong Electronics Co. 2017), which refers to sensors of a digital type and makes it possible to measure the following:

- temperature in the range from −40 to +80°C with a total absolute error of not more than ±0.5°C, which meets the requirements set above (Laktionov et al., 2017a, 2017b); and
- humidity in the range from 0 to 100% with a total absolute error of not more than ±2%, which meets the previously stated requirements (Laktionov et al., 2017a, 2017b).

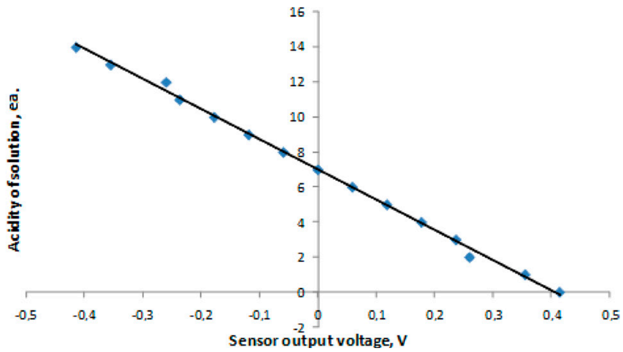

Figure 4: Solution acidity sensor conversion characteristics during irrigation.

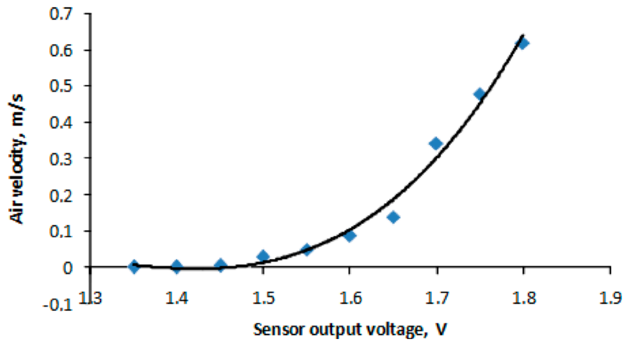

Figure 5: Conversion characteristics of the air velocity sensor.

The prototype and equivalent circuit diagrams for the replacement of humidity MCh and temperature of the DHT22 sensor are shown in Figures 8,9, respectively.

Measuring channel of air velocity in the cultivation area (V_{air})

The MCh is based on the microcircuit of the low-cost thermoresistive anemometer of the type Rev. P Wind Sensor (Badger, 2017), which allows measuring in the range from 0 to 0.7 m/sec with a total relative error of not more than ±3% under regular conditions, which meets the requirements stated above (Laktionov et al., 2017a, 2017b). The connection scheme of the prototype model and the equivalent circuit diagram of connecting this sensor to the microprocessor platform are shown in Figures 8,9, respectively. The graphical form of the air velocity sensor conversion characteristics obtained from the results of laboratory tests is shown in Figure 5.

The empirical formula Shown below is obtained by regression analysis. It describes the characteristics (see Fig. 5), with the coefficient of determination $R^2 = 0.987$:

$$V_{air} = 5.466 \cdot U_{Vair}^3 - 20.86 \cdot U_{Vair}^2 + 26.18 \cdot U_{Vair} - 10.76, \qquad (4)$$

where V_{air} – speed of air streams in the cultivation area, m/sec; U_{Vair} – output voltage of the air speed sensor, V.

Measuring channel of soil moisture (W_{soil}) in the root layer

This MCh is based on the conductometric module, which consists of YL-69 contact probe and YL-38 sensor (Soil Moisture Sensor Hookup Guide, 2017), which allows measuring in the range of 10 to 100% at a qualitative level. The prototype and equivalent circuit diagram are shown in Figures 8,9, respectively. The graphical view of the qualitative characteristics of the soil moisture sensor conversion obtained on the basis of laboratory tests is shown in Figure 6.

Measuring channels of soil temperature (T_{soil}) and solution temperature ($T_{solution}$)

These measuring channels are built on the basis of NTC thermistors of the B57891M0103J000 type with a nominal resistance of 10000 Ohm (NTC Thermistors, 2017), which refer to sensors of the parametric type and are included in the circuits of the corresponding voltage dividers, as shown in the microprocessor system diagram in Figures 8,9. A technological difference of the field implementation of these measuring channels is the use of a moisture-proof housing for the solution temperature sensor during irrigation. This type of sensor allows measuring in the range of 15 to 30°C with a total relative error of not more than ±5%. The graphical view of the conversion characteristics obtained on the basis of laboratory tests is shown in Figure 7.

The empirical formula shown below is obtained by regression analysis. It describes the characteristics (see Fig. 7), with the coefficient of determination $R^2 = 0.983$:

$$t = 33.94 \cdot \exp(-0.03 \cdot R_t) \qquad (5)$$

where t – temperature of the corresponding environment, C; R_t – thermistor resistance, Ohm.

Microprocessor platform

The Arduino Mega 2560 board is used as the microprocessor module of the system under investigation.

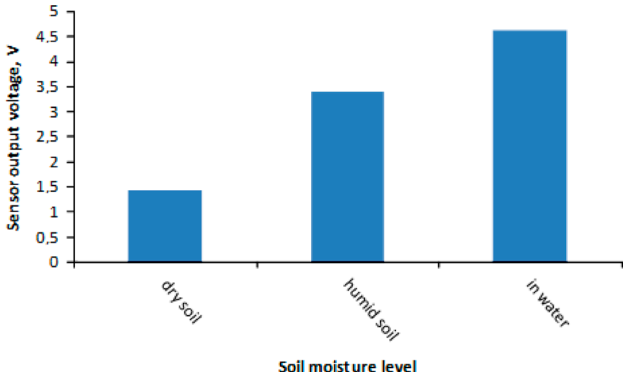

Figure 6: The qualitative characteristics of the soil moisture sensor conversion.

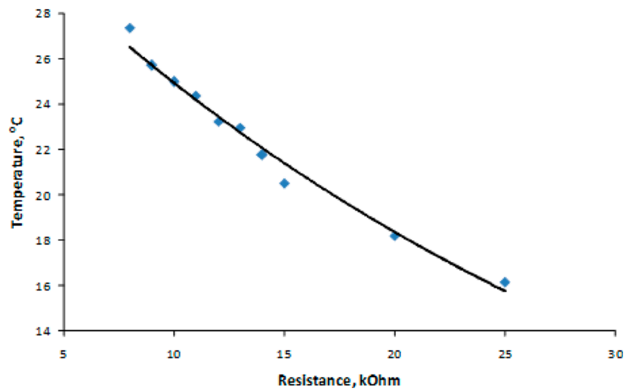

Figure 7: Thermistor conversion characteristics.

It is based on the ATmega 2560 microchip with a frequency of 16 MHz (Arduino Mega 2560, 2017). This board is chosen on the basis of the following criteria: the required number of analog inputs (more than seven, which corresponds to the number of sensors of physical and chemical parameters regardless of DHT22 temperature and humidity sensor, which uses one digital input), Flash storage capacity (more than 64 KB, which corresponds to the size of the original sketch) and cost. Physical configuration and connection diagram are shown in Figures 8,9, respectively.

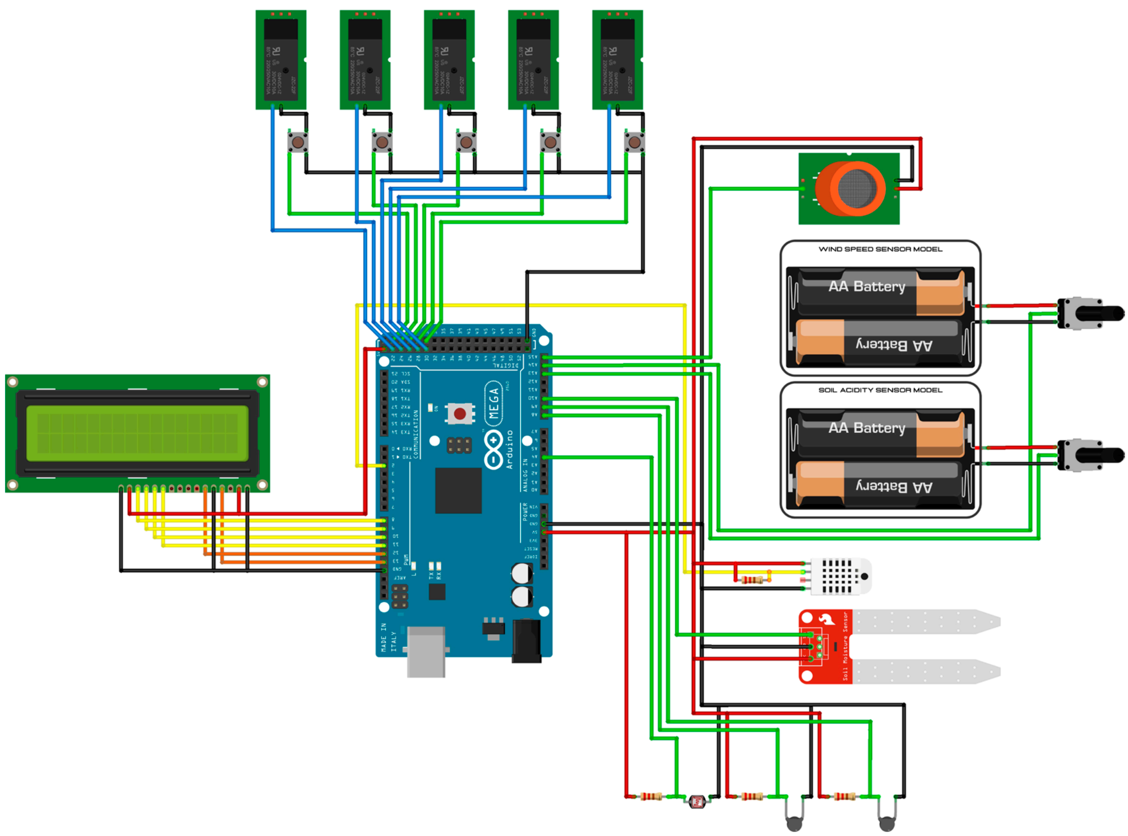

Figure 8: The results of prototyping the microprocessor system.

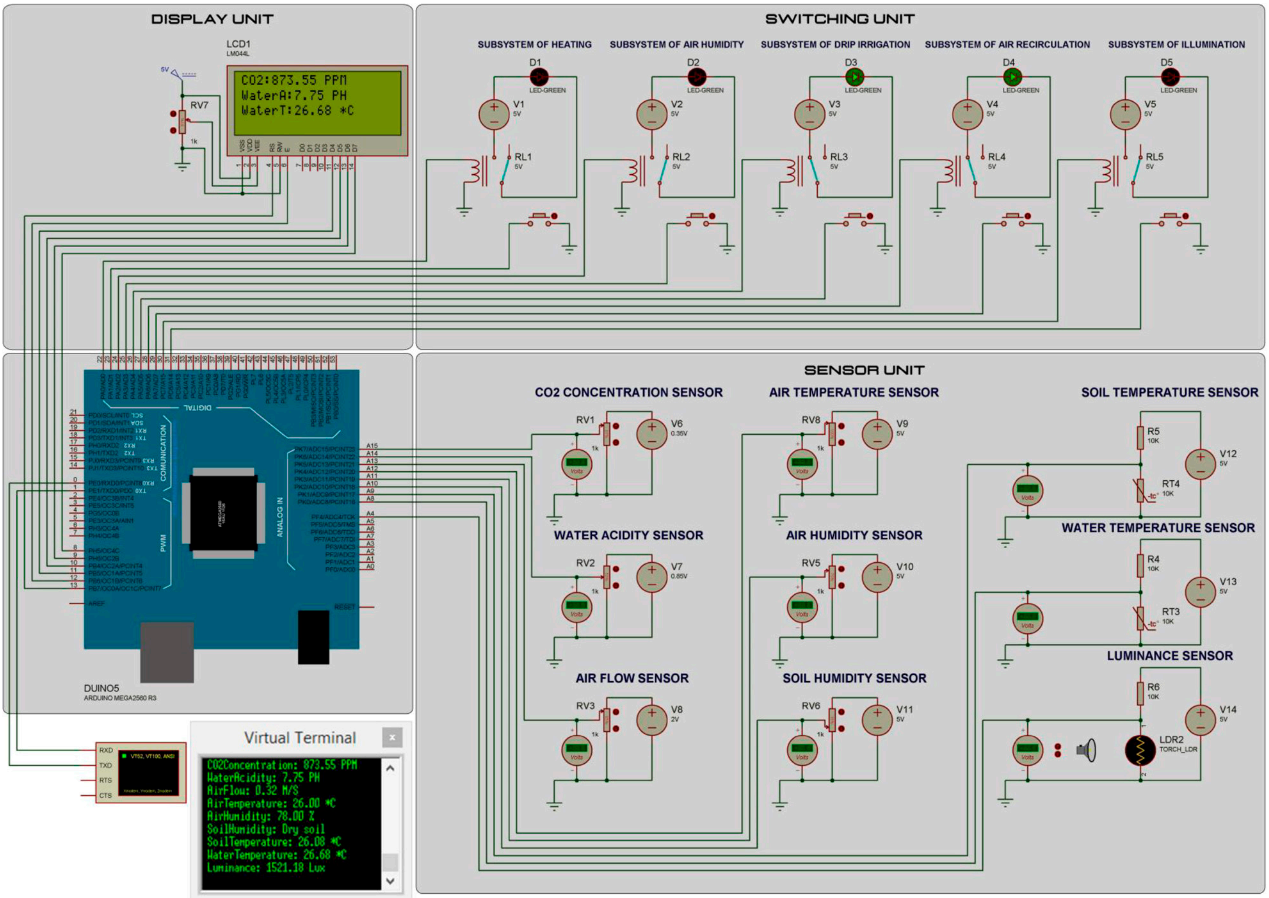

Figure 9: The simulation model of the system under study.

LCD

The visualization unit of the measuring information is implemented on LM044L LCD type (HITACHI LM044L, 2017) on the basis of Samsung KS0066 chip with the ability to readout information in 4 lines of 20 characters each. Physical configuration, the board connection scheme and the results of work are presented in Figures 8,9, respectively.

Relay block

As a switching unit for the power load, the SONGLE SRD-05VDC relay module, which is widely spread in the Arduino area, is used (Songle Relay, 2017). This relay is controlled by voltage of 5 V and is able to commute the load with parameters up to 10 A–30 V DC voltage. The number of relay blocks is five, which corresponds to the main controllable modules (technological processes: drip irrigation, ventilation, artificial lighting, heating and humidification of air). The physical configuration and connection diagram of this functional node are shown in Figures 8,9, respectively.

Software

Approaches underlying the study of the computerized monitoring and control system for the greenhouse microclimate parameters are based on modern achievements in the theory of information and measurement systems, theories of simulation, physical and mathematical modeling, probability theory and mathematical statistics, as well as experimental methods for studying the prototype multi-channel system. To implement the main stages of development and research of the monitoring and control system for the industrial greenhouse microclimate parameters, the following modern software is used: regression analysis of the sensor conversion characteristics for physical and chemical parameters of the greenhouse microclimate is based on MS Excel and Mathcad; visualization

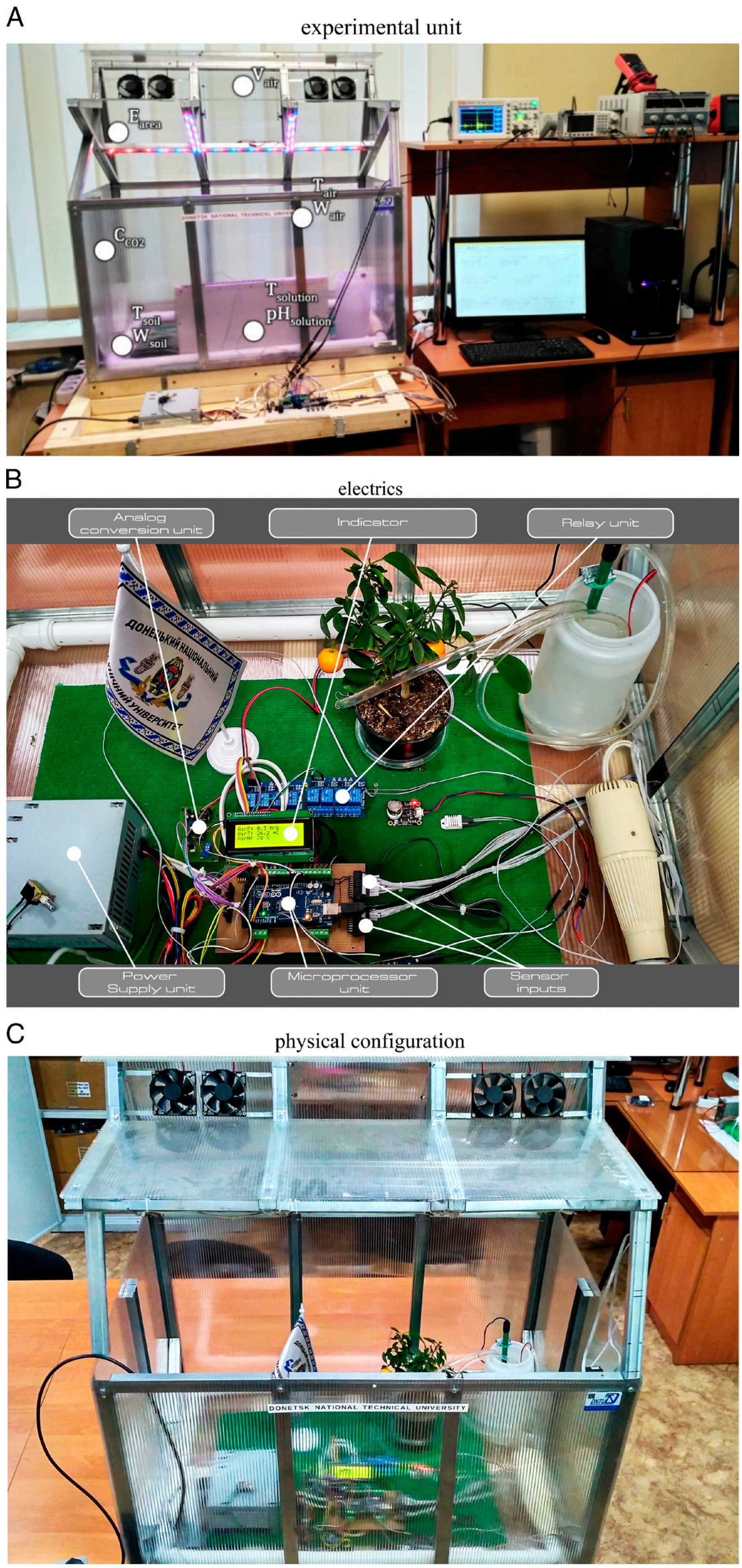

Figure 10: Photo of the laboratory facility for the study of the dynamics of greenhouse microclimate parameters.

Initial settings and port configurations → ***Cyclic sampling of the system measuring channels and calculating of the physical and chemical microclimate parameters*** → ***Indication of monitoring results*** → ***Controlof technological modes***

```
#include "math.h"
#include <LiquidCrystal.h>
#include "stDHT.h"
LiquidCrystal lcd(13, 12, 11, 10, 9, 8);
DHT sens(DHT22);
int SensorCO2ConcentrationPin = A15;
int SensorCO2ConcentrationValue;
float U_CO2Concentration;
float CO2Concentration;
int SensorWaterAcidityPin = A14;
int SensorWaterAcidityValue;
float U_WaterAcidity;
float WaterAcidity;
int SensorAirFlowPin = A13;
int SensorAirFlowValue;
float U_AirFlow;
float AirFlow;
float AirTemperature;
float AirHumidity;
int SensorSoilHumidityPin = A10;
int SensorSoilHumidityValue;
float U_SoilHumidity;
float SoilHumidity;
int SensorSoilTemperaturePin = A9;
int SensorSoilTemperatureValue;
float U_SoilTemperature;
float R_SoilTemperature;
float SoilTemperature;
int SensorWaterTemperaturePin = A8;
int SensorWaterTemperatureValue;
float U_WaterTemperature;
float R_WaterTemperature;
float WaterTemperature;
int SensorLuminancePin = A4;
int SensorLuminanceValue;
float U_Luminance;
float R_Luminance;
float Luminance;
int RelayPin_1= 22;
int RelayPin_2= 24;
int RelayPin_3= 26;
int RelayPin_4= 28;
int RelayPin_5= 30;
int dht_pin=2;
const int ButtonPin_1= 23;
int ButtonState_1= 0;
const int ButtonPin_2= 25;
int ButtonState_2= 0;
const int ButtonPin_3= 27;
int ButtonState_3= 0;
const int ButtonPin_4= 29;
int ButtonState_4= 0;
const int ButtonPin_5= 31;
int ButtonState_5= 0;
int R1= 10;
int R2= 10;
int R3= 10;
void setup()
{
  Serial.begin(9600);
  lcd.begin(20, 4);
  pinMode(RelayPin_1, OUTPUT);
  pinMode(RelayPin_2, OUTPUT);
  pinMode(RelayPin_3, OUTPUT);
  pinMode(RelayPin_4, OUTPUT);
  pinMode(RelayPin_5, OUTPUT);
  pinMode(ButtonPin_1, INPUT);
  pinMode(ButtonPin_2, INPUT);
  pinMode(ButtonPin_3, INPUT);
  pinMode(ButtonPin_4, INPUT);
  pinMode(ButtonPin_5, INPUT);
  pinMode(dht_pin, INPUT);
}
```

```
void loop()
{
     SensorCO2ConcentrationValue =
analogRead(SensorCO2
ConcentrationPin);
     U_CO2Concentration = SensorCO2
ConcentrationValue*5.0/1023.0;
     float x = pow(10,6);
     float y = pow(2.71,(-53.8*U_CO2
Concentration));
     CO2Concentration = x*y*10000;
     SensorWaterAcidityValue =
analogRead(SensorWaterAcidityPin);
     U_WaterAcidity =
SensorWaterAcidityValue*5.0/1023.0;
     WaterAcidity = -17.24
*U_WaterAcidity+7;
     if (WaterAcidity < 0)
     {
       WaterAcidity = abs(WaterAcidity)+7;
     }
     SensorAirFlowValue =
analogRead(SensorAirFlowPin);
     U_AirFlow = SensorAirFlowValue*5.0/
1023.0;
     AirFlow = 5.466
*U_AirFlow*U_AirFlow*U_AirFlow-20.86
*U_AirFlow*U_AirFlow+26.18*U_AirFlow-
10.76;
     AirTemperature =
sens.readTemperature(dht_pin);
     AirHumidity =
sens.readHimidity(dht_pin);
     SensorSoilHumidityValue =
analogRead(SensorSoilHumidityPin);
     U_SoilHumidity =
SensorSoilHumidityValue*5.0/1023.0;
     SoilHumidity = U_SoilHumidity;
     SensorSoilTemperatureValue =
analogRead(SensorSoilTemperaturePin);
     U_SoilTemperature =
SensorSoilTemperatureValue*5.0/1023.0;
     R_SoilTemperature = R1
*U_SoilTemperature/(5-
U_SoilTemperature);
     float x_1= pow(2.71,(-0.03
*R_SoilTemperature));
     SoilTemperature = 33.94*x_1;
     SensorWaterTemperatureValue =
analogRead(SensorWaterTemperaturePin
);
     U_WaterTemperature =
SensorWaterTemperatureValue*5.0/
1023.0;
     R_WaterTemperature = R2
*U_WaterTemperature/(5-
U_WaterTemperature);
     float x_2= pow(2.71,(-0.03
*R_WaterTemperature));
     WaterTemperature = 33.94*x_2;
     SensorLuminanceValue =
analogRead(SensorLuminancePin);
     U_Luminance =
SensorLuminanceValue*5.0/1023.0;
     R_Luminance = R3*U_Luminance/(5-
U_Luminance);
     float x_3= pow(2.71,(-0.03
*R_Luminance));
     Luminance = pow(10,(5.803*x_3));
```

```
lcd.setCursor(0, 0);
     lcd.print("CO2:");
     lcd.print(CO2
Concentration);
     lcd.print(" PPM");
     lcd.setCursor(0, 1);
     lcd.print("WaterA:");
     lcd.print(WaterAcidity);
     lcd.print(" PH");
     lcd.setCursor(0, 2);
     lcd.print("WaterT:");

lcd.print(WaterTemperature)
;
     lcd.print(" *C");
     delay(1000);
     lcd.clear();
     lcd.setCursor(0, 0);
     lcd.print("AirF:");
     lcd.print(AirFlow);
     lcd.print(" M/S");
     lcd.setCursor(0, 1);
     lcd.print("AirT:");

lcd.print(AirTemperature);
     lcd.print(" *C");
     lcd.setCursor(0, 2);
     lcd.print("AirH:");
     lcd.print(AirHumidity);
     lcd.print(" %");
     delay(1000);
     lcd.clear();
     lcd.setCursor(0, 0);
     lcd.print("Lum:");
     lcd.print(Luminance);
     lcd.print(" Lux");
     lcd.setCursor(0, 1);
     lcd.print("SoilT:");

lcd.print(SoilTemperature);
     lcd.print(" *C");
     lcd.setCursor(0, 2);
     lcd.print("SoilH:");
     if (U_SoilHumidity < 1.5)
     {
       lcd.print("Dry soil");
     }
       else if (U_SoilHumidity
>= 1.5&& U_SoilHumidity <
3.4)
       {
         lcd.print("Humid soil");
       }
       else
       {
         lcd.print("In water");
       }
     delay(1000);
     lcd.clear();
```

```
ButtonState_1=
digitalRead(ButtonPin_1);
     ButtonState_2=
digitalRead(ButtonPin_2);
     ButtonState_3=
digitalRead(ButtonPin_3);
     ButtonState_4=
digitalRead(ButtonPin_4);
     ButtonState_5=
digitalRead(ButtonPin_5);
 if (ButtonState_1== LOW ||
(AirTemperature < 20))
     {
       digitalWrite(RelayPin_1,
HIGH);
     }
     else digitalWrite(RelayPin_1,
LOW);
       {
         if (ButtonState_2== LOW ||
(AirHumidity < 70))
       {
         digitalWrite(RelayPin_2,
HIGH);
       }
       else digitalWrite(RelayPin_2,
LOW);
         {
           if (ButtonState_3== LOW ||
(SoilHumidity < 1.5))
         {
           digitalWrite(RelayPin_3,
HIGH);
         }
         else digitalWrite(RelayPin_3,
LOW);
           {
             if (ButtonState_4== LOW ||
(AirTemperature > 25))
           {
             digitalWrite(RelayPin_4,
HIGH);
           }
           else digitalWrite(RelayPin_4,
LOW);
             {
               if (ButtonState_5== LOW
|| (Luminance < 10))
             {
               digitalWrite(RelayPin_5,
HIGH);
             }
             else digitalWrite(RelayPin_
5, LOW);
             }
           }
         }
       }
  delay(2000);
}
```

Figure 11: The software component of the monitoring and control system under research.

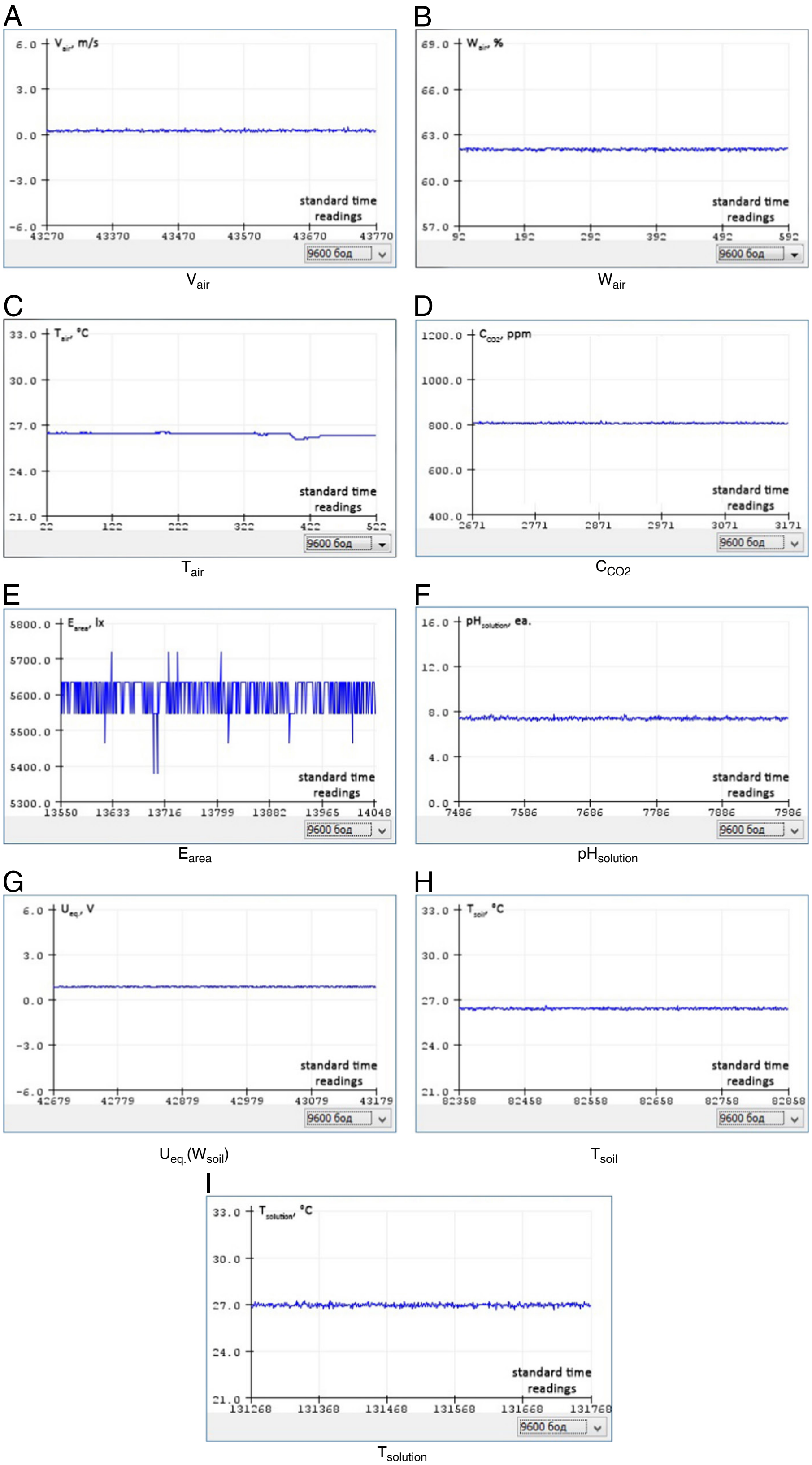

Figure 12: Results of laboratory tests of the system under research.

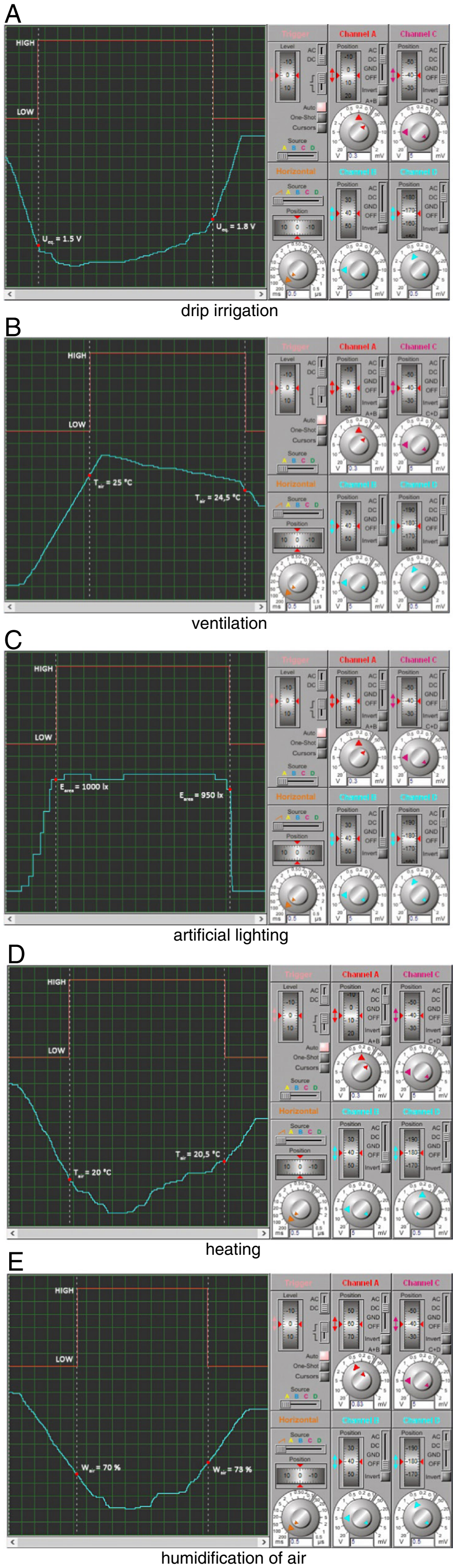

Figure 13: Results of the simulation model testing.

of the physical configuration of the microprocessor system is based on the Fritzing software product; the simulation model of the microprocessor system is developed and studied in the environment of Proteus 8.0 (hardware component) and Arduino IDE (software component); graphical interpretation of the laboratory tests results of the microprocessor system physical model is based on the Plotter COM-port Arduino IDE function.

Findings

The procedure for visualizing the physical configuration of the microprocessor system for monitoring and controlling the microclimate parameters of industrial greenhouses using the hardware components analyzed in the Section "Materials and methods" is performed in the Fritzing, which allows virtual prototyping and modeling of electronic devices of various complexity levels with open source code. This stage of the research makes it possible to increase the ergonomics index of the procedure for developing the hardware component of the microprocessor system and to synthesize its scheme. The results of prototyping of the system under study are shown in Figure 8.

Having obtained the results of prototyping (see Figure 8) and regression analysis of the conversion characteristics of the sensor for measuring the greenhouse microclimate parameters (see Figs. 2–7) in the Proteus 8.0 software package for computer-aided design, the simulation model of the system under study, which is shown in Figure 9, has been implemented and tested.

Taking into account the developed software (see Fig. 11), the main simulation results have been obtained and analyzed (see Fig. 9, Virtual terminal). A characteristic feature of approaches to modeling is the use of regulated voltage sources as sensor models (see Fig. 9, Sensor unit: RV_1–V_6, RV_2–V_7, RV_3–V_8, RV_8–V_9, RV_5–V_{10}, RV_6–V_{11}, R_5–RT_4–V_{12}, R_4–RT_3–V_{13}, R_6–LDR_2–V_{14}), which allow simulating sensor operation based on their conversion characteristics (see Figs. 2–7) under the limitations of the standard libraries of the Proteus simulation environment.

The implemented model enables us to control the technological regimes of vegetable cultivation in manual and automatic modes, namely: monitoring and interacting with sensors of physical and chemical parameters, aggregation of observation results in the database, switching on/off control elements by threshold value of measured quantity and/or by pressing the button (see Fig. 9, Switching Unit).

The implementation of this research stage enabled optimization of the structure and software of the physical model of the microprocessor system for monitoring and controlling the microclimate parameters, as shown in Figures 10, 11, respectively. The results of laboratory tests, which are presented in Figure 12 (V_{air}=0.3±0.01 m/s, W_{air}=62±1%, T_{air}=25.5±0.5°C, C_{CO_2}=820±10 ppm, E_{area}=5570±150 lux, $pH_{solution}$= 7.1±0.1 ea., $U_{eq.}$=$f(W_{soil})$=1.1±0.05 V, T_{soil}=26±0.5°C, $T_{solution}$=27±0.5°C), prove the satisfactory convergence (deviation does not exceed ±7%) of the results of simulation and full-scale experimental studies of the physical model of the computerized system under study.

The results of the simulation model testing, which confirm the operability and adequacy of monitoring and control methods for plant growth regimes, are presented in Figure 13.

The analysis of the obtained system operation oscillograms (see Fig. 13) confirm the adequacy of the proposed methods and models of the computerized microclimate parameters' monitoring and control for industrial greenhouse conditions. Inconsistency of the operation levels of control process (delay is equal from 100 to 400 ms) is due to the imperfection of the relay blocks models in Proteus computer-aided design. These structural components have an inductive component of the total resistance. This level difference is within the permissible error.

The research results obtained in this paper are the basis for further experimental studies to increase the informative value of the process of computerized monitoring and controlling the microclimate parameters of industrial greenhouse complexes in the following promising areas:

- introducing adaptive high-performance methods and tools for collecting and processing measurement information on the dynamics of physical and chemical parameters of the greenhouse microclimate in real time mode; and
- implementing scientific and theoretical studies and practical research on establishing complex influence of the greenhouse microclimate parameters distributed in space and time on the indicators of quality, rates and volumes of vegetable production under greenhouse conditions.

The obtained results can be integrated into the methods and means of the computerized monitoring and control of automatic stationary complexes for the industrial greenhouses' conditions. Also, the results of the paper can be used for adaptive computerized meters development for measuring monitoring and control of agro-industrial complex objects' parameters.

Discussion and conclusions

The research results, obtained in this paper, are devoted to the solution of the current scientific and applied problem concerning limited existing results of studies on the effectiveness of computerized monitoring and controlling the technological processes of protected vegetable cultivation involving simulation modeling methods by means of modern hardware and software. As a result, scientific and practical approaches to the development and research of hardware and software for computerized monitoring and controlling the microclimate parameters of industrial greenhouses have been substantiated, which, in comparison to the existing ones, satisfy the complexity condition. The following stages of system development are taken into account: regression analysis of the sensor conversion characteristics, prototyping of the system, simulation and physical modeling of the microprocessor system, qualitative and quantitative analysis of research results. Also, the developed methods and tools are adaptive to the crops types and periods of their vegetation, in contrast to other existing approaches. The main scientific and practical results of the research are: regression analysis of experimental characteristics of the system measuring channels conversions; development and testing of prototyped, simulation and physical models of a computerized monitoring and control system for the greenhouse microclimate parameters; substantiation of promising directions of further research on hardware and software implementation of the computerized system through its laboratory experimental testing, followed by aggregation and mathematical processing of measurement results.

The developed simulation model can be used as a tool for research on optimization of structural and algorithmic organization of computerized monitoring and control systems of greenhouse microclimate parameters. The future work would be to use more statistical data for the development of prediction models, which will be analyzed in the cloud side using IoT and Data Mining technologies. The researches on models development for control of growing crops' technological regimes based on fuzzy logic method should also be carried out. The research works on the evaluation of energy and economic performance of the system is necessary to perform in the near future.

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