# Development the neuro-controller of processing technological data for the control system of the enterprise energy efficiency (#83584)



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# Development the neuro-controller of processing technological data for the control system of the enterprise energy efficiency

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## Abstract

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**Subjects** Data Mining and Machine Learning, Neural Networks

**Keywords** Energy efficiency, Neuro-controller, Artificial neural network, STM32, Intelligent mini-greenhouse, Control system

## INTRODUCTION

In the processing of technological data from sensors in multilevel control system for energy efficiency of the enterprise (MCSEE) (Knayer & Kryvinska, 2022; Teslyuk et al., 2022; Teslyuk et al., 2017), their loss often occurs, there is a need to process fuzzy data, etc. In such situations, it is advisable to use special intellectual tools. For example, in this work it is proposed to process the technological data using a microcontroller with a neural network implemented by software. It is clear that for most technical problems such a combination is sufficient in terms of speed, and for real-time systems the neural network can be implemented at the hardware level (Kravets & Shymkovych, 2020; Mishchuk, Tkachenko & Izonin, 2020).

Accordingly, the purpose of the work is the developing of neuro-controller for processing technological data (NPTD) in the energy efficiency management system of the enterprise. To achieve the set goal, it is necessary: to develop the structure and algorithm of NPTD functioning; to develop a model on the basis of artificial neural network for processing of technological data in MCSEE; to develop program and hardware means of NPTD.

The article includes the analyzing of existing solutions of the specified problem, the development of the functioning algorithm and structure of neuro-controller, which is based on the modular principle. The built ANN model is developed and tested. The peculiarities of the hardware and software implementation of the neuro-controller are also given.

## Related works

Modern trends in industry, consisting in the application of Industry 4.0 (Zaimovic, 2019; Oztemel & Gursev, 2020; Nascimento et al., 2019), the large-scale use of smart systems in various spheres of human activity (Kim et al., 2022; Mazza, Tarchi & Juan, 2022; Mbungu, Bansal & Naidoo, 2019) are aimed at saving energy carriers and increasing energy efficiency.

The above-mentioned concept can be practically realized with the use of modern technologies, methods and models of computing intelligence. Most enterprises, firms and organizations use the multi-level energy efficiency management systems of the enterprise or region to improve energy efficiency. To date, a number of ISA-95, IEC 62264, ANSI/ISA-95 and IEC 62264 standards have been developed that define requirements and features in the development of such systems (Wally, Huemer & Mazak, 2017; International Electrotechnical Commission, 2013; International Electrotechnical Commission, 2018; International Electrotechnical Commission, 2016).

As a rule, such energy efficiency management systems are multi-level and hierarchical (Teslyuk et al., 2022; Teslyuk et al., 2017). The level of data collection and management of executive mechanisms is located closest to technological processes and controls technological parameters with the help of sensors. Technological data are fuzzy and unstructured and accordingly their effective processing is possible using artificial neural networks (Wally, Huemer & Mazak, 2017;

International Electrotechnical Commission, 2013; International Electrotechnical Commission, 2018). In particular, Teslyuk et al. (2022) proposed a device based on the neuro-controller, where an artificial neural network is implemented in the form of a program that controls the operation of the microcontroller and the implemented artificial neural network (ANN).
Engineers widely use neuro-controllers in the process of solving technical tasks, where the problem of processing fuzzy input data arises. In particular, this problem arises in construction (Chang & Sung, 2019; Zizouni et al., 2019) – for seismic exploration problems; in the process of implementing smart home systems (Teslyuk et al., 2019; Teslyuk et al., 2018) – for the tasks of protecting the building and processing emergency situations; in materials science (González-Yero et al., 2021), etc.
The conducted analysis makes it possible to state that the implementation of ANN is possible with two approaches: software (Chang & Sung, 2019; Zizouni et al., 2019; Teslyuk et al., 2019; Teslyuk et al., 2018; González-Yero et al., 2021) and hardware (Chang, Martini & Culurciello, 2015; Nurvitadhi et al., 2017). The software approach consists in the software implementation of the ANN, which is stored in the microcontroller memory. This approach is more commonly used in practice and makes it possible to change the parameters of the network model during the operation of the neuro-controller, which is an advantage of this approach. At the same time, for real-time systems, it is necessary to use hardware implementation of ANN to ensure strict requirements for the performance of the designed system. But at the same time, it will be much more difficult to make changes to the network structure. It is proposed to increase the operation performance of the ANN model taking into account their hardware implementation, using FPGA, CPU, and GPU (Misra & Saha, 2010, Nurvitadhi et al., 2016; Ovtcharov et al., 2015). But such hardware implementation has worse values of both weight and size, and economic parameters.
Accordingly, this paper uses the first approach to the implementation of the ANN and storing the program in the memory of a standard microcontroller. This makes it possible to provide the requirements for performance, cost and size parameters in the process of collecting and previous processing technological data in the MCSEE.

## MATERIALS & METHODS

### Development of the structure and algorithm of the functioning of an intelligent data collection and processing tool

In general, the developed structure of the basic neuro-controller includes three main components, in particular: a subsystem for collecting data about the environment; a subsystem for processing input technological data; a subsystem of influence on the studied environment.
In mathematical form, the corresponding structure can be written using the following tuple:

$$Ne_{contr} = \langle M_{sensors}, M_{hard-softwore}, M_{actuators}, M_{\mathrm{ints}} \rangle, \quad (1)$$

where $M_{sensors}$ is a set of sensors and detectors; $M_{hard-softwore}$ is a set of hardware and software tools; $M_{actuators}$ is a set of actuators that make it possible to influence the studied environment and $M_{\text{int}s}$ is an incidence matrix that allows establishing relationships between sensors, software and hardware, and actuators.

Let's consider a typical intelligent data processing tool using the example of the implementation of the intelligent mini-greenhouse control system (Ma, Li & Yang, 2018; Suryawanshi et al., 2018). The intelligent greenhouse provides maintenance of the microclimate and lighting regime for growing plants according to the specified conditions. We implement the corresponding subsystem on the basis of the developed neuro-controller. The developed structure of the control system (Batyuk, Voityshyn & Verhun, 2018) includes the following components (Fig. 1): a microcontroller that contains a control program and a developed neural network for analyzing technological data and generating control signals for making management decisions. The control system includes sensors, namely:

- air temperature sensor for monitoring the temperature regime in the environment;
- air humidity sensor for tracking the water vapor content in the air;
- soil moisture sensor to monitor soil moisture;
- light sensor for tracking the level of outdoor lighting;
- system timer for tracking the time of day.

The block diagram of the algorithm of the neuro-controller for controlling the intelligent mini-greenhouse is shown in Fig. 2.

The above sensors make it possible to determine changes in the mini-greenhouse environment (Ma, Li & Yang, 2018; Suryawanshi et al., 2018). The actuators were used to influence the medium of the greenhouse. In particular, the developed intelligent greenhouse control system (Batyuk, Voityshyn & Verhun, 2018) uses the following actuators (executive modules): the subsystem of watering of the soil; the ventilation subsystem to reduce temperature and humidity inside the air control and cleaning system; the subsystem of heating air; the lighting subsystem that turns on in case of insufficient external light.

For the case of the structure shown in Fig. 1, the set of sensors includes elements, namely:

$$M_{sensors} = S_1, S_2, S_3, S_4,$$

where $S_1$ is the air temperature sensor; $S_2$ is the air humidity sensor; $S_3$ is the soil moisture sensor; $S_4$ is the illumination sensor of the medium of mini-greenhouse.

**Figure 1. Structure of the control subsystem of intelligent mini-greenhouse**

A set of hardware and software tools includes only two components: a microcontroller and software that emulates the operation of an artificial neural network. It should be noted that the appropriate set may include several microcontrollers, which is determined by technical and economic feasibility. The set of actuators also includes four elements (modules):

$$M_{actuator} = A_1, A_2, A_3, A_4,$$

where $A_1$ is a module that implements the function of watering a controlled environment; $A_2$ is a module that provides ventilation of the environment; $A_3$ and $A_4$ heating module and lighting module, respectively.

The incidence matrix for the studied structure of the system in Fig. 1 makes it possible to display the connections between structural elements. It has the following form:

$$M_{ints} = \begin{vmatrix} 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{vmatrix}.$$

**Figure 2. Block diagram of the neuro-controller algorithm for controlling an intelligent mini-greenhouse**

The algorithm of the neuro-controller operation includes several basic steps (Fig. 3). The developed algorithm provides an initial step, which is designed to establish initial data (system initialization, port initialization, etc.). The following steps are performed sequentially in the cycle: polling and receiving technological data from sensors; the step related to the processing of the received data from sensors by a neural network and the step of forming control signals for the subsystem of influence on the studied environment.

**Figure 3. A simplified block diagram of algorithm of neuro-controller operation**

Representation of the structural model of the system in the graph form (2) makes it possible to analyze the functioning of the system using existing free software systems.

$$G = (P, I), \tag{2}$$

where $P$ is a set of nodes (components) and $I$ is a set of arcs.

To analyze the operation of the intelligent mini-greenhouse control system, it is advisable to use a structural model in the form of a graph (Fig. 4).

**Figure 4. Structural model of the intelligent mini-greenhouse control system in the graph form**

## Development, training and features of implementation of the artificial neural network model

**Building models of the functioning scenarios of intelligent tools of collecting and processing technological data**

Models of system operation scenarios can be described using a number of conditions that are determined by operation modes. Therefore, it is necessary to maintain the temperature regime in the environment of the intelligent mini-greenhouse and the level of illumination during the hours set aside for this. We introduce the following notations, respectively: $T$ is a temperature inside the system; $H_{earth}$ is the soil moisture; $H_{air}$ is an air humidity; $L$ is the level of external lighting; $D$ is the time of day (0-24 hours).

During the functioning of the intelligent mini-greenhouse, the following conditions must be maintained:

$$T_{min} < T < T_{max},\ H_{earth\,min} < H < H_{earth\,max}, \tag{3}$$
$$H_{air\,min} < H < H_{air\,max},\ L_{min} < L < L_{max},\ D_{min} < D < D_{max},$$

where $T_{min}$, $T_{max}$ – minimum and maximum temperature value; $H_{earth\,min}$, $H_{earth\,max}$ – minimum and maximum soil moisture value; $H_{air\,min}$, $H_{air\,max}$ – minimum and maximum value of air humidity; $L_{min}$, $L_{max}$ – minimum and maximum value of the level of exterior light; $D_{min}$, $D_{max}$ – minimum and maximum value of time of day.

To support the above modes, it is necessary to develop system operation scenarios that describe the necessary actions to stabilize conditions in the mini-greenhouse environment. Work scenarios include steps that are described and summarized in the Table 1.

**Table 1. Work scenarios of intellectual greenhouse**

So, the neural network receives technological data from sensors of temperature, soil moisture and light sensor. The mode of watering and lighting depends on the time of day. The neuro-controller generates control signals for controlling ventilation shafts, heaters, lighting and watering. Accordingly, the resulting neural network model should have four inputs and four outputs.

**Data preparation for neural network training and testing**

To train the neural network, a set of data is generated that describe the received values from the sensors and the expected values for the actuators. For training, it is necessary to generate a sufficient sample that will represent the various states where the system can be in.

A special Java program was developed to prepare a set of data and its normalization. The built program randomly selects the values of the sensors and analytically calculates the expected values on the actuators.

The generated data sets must be normalized so that the values are in the range [0..1]. For this purpose, at the 2nd stage, the program runs the developed normalization module and outputs the final results. The example of the main class code for data normalization is shown in Fig. 5.

**Figure 5. An example of the main class code for data normalization**

An example of the generated training sample for training a neural network is shown in Fig. 6.

**Figure 6. A fragment of the training sample**

**Peculiarities of implementation and training of an artificial neural network**

The NeurophStudio environment was used for designing, training and checking the functioning correctness of the neural network. This is a free program for designing neural networks of various types. The program allows to monitor the learning process, modify the structure of the neural network, determine a set of training values, visualize the learning results, etc. A multilayer perceptron was chosen as a neural network.

In the NeurophStudio environment a neural network is designed. It consists of 4 input neurons and one balancing neuron, 6 internal neurons and one balancing neuron. The output layer contains 4 neurons.

Within the environment, the structure and connections between neurons can be explored. For correct training of the neural network, it is recommended to divide the set into 2 parts. The first part is used to train the neural network, while the second part is a control set that can be used to test the neural network on new data. In this case, neural network training takes place on 80% of the data set.

The training of neural network of multilayer perceptron is carried out by the method of backpropagation of the error. An example of the dependence of the neural network learning error on the number of iterations is shown in Fig. 7 and Fig. 8.

**Figure 7. Results of neural network training, iterations 1-2000**

The neural network is tested on 20% of the data that was not involved during the training process. This means that the neural network was not specially trained, and the results of work on this sample provide an opportunity to check how the neural network functions on independent data.

As a result of checking the accuracy of the functioning of the neural network for the control of the intelligent mini-greenhouse, the mean squared error value of 0.032 was obtained. After that, the trained neural network is used in the process of practical implementation of the neuro-controller.

**Figure 8. Results of neural network training, iterations 2001-6000**

# RESULTS AND DISCUSSION

## Hardware and software implementation of the basic neuro-controller

The development of a basic neuro-controller includes two main parts, namely: hardware and software.

### Features of the hardware implementation of the neuro-controller

We developed a structural diagram of the hardware part of the basic neuro-controller, which includes the following components (Fig. 9):

- microcontroller STM32-F103C8T6 (Ma, Li & Yang, 2018; Suryawanshi et al., 2018; Chudzik, 2015), which is based on the core: ARM 32 Cortex-M3 with an operating frequency 72 MHz, the volume of 64 kb of program memory and 20 kb of flash memory;
- system timer DS1307, which is necessary to determine the time of day;
- a number of sensors were used to monitor technological data on microclimate and lighting:
  - temperature sensor DS18B20, which makes it possible to monitor the temperature in the range from – 10 C to 85 C with an error of 0.5 C;
  - temperature and humidity sensor DHT11, which allows to monitor air humidity in the range from 20% to 80% with an error of 5%. Also, the sensor allows to monitor the temperature in the range from 0 C to 60 C with an error of 2%. The DS18B20 sensor gives a value with a smaller error, so it is recommended to use it in contrast to the DHT11;
  - soil moisture sensor that measures soil conductivity and provides data in the range of 0-5V depending on the set threshold value;
  - photoresistor, on the basis of which the light sensor is organized and an auxiliary balancing resistor is used. The change in the voltage ratio between the balancing resistor and the photoresistor is determined by external lighting.
  - relays are used as executive devices. The relay is used to control the power supply of the actuators.

**Figure 9. Structural diagram of the hardware of the intelligent mini-greenhouse control system**

The EasyEDA tool was used to design the hardware implementation. The development environment makes it possible to synthesize the electrical schematic diagram and the connection diagram of the components on the circuit board (Fig. 10).

**Figure 10. Scheme of the hardware implementation of the neuro-controller**

The basic electrical diagram shows the structure of the ports of each of the elements and the diagram of connecting the components to each other.

### Software implementation of the neuro-controller

The software implementation of the neuro-controller includes several modules, each of which is responsible for a certain aspect of the neuro-controller operation. The software consists of the following modules (Fig. 11).

**Figure 11. Software structure of the intelligent mini-greenhouse management system**

The system initialization module is responsible for: preliminary system initialization; initialization of ports for work with sensors, actuators and system timer; loading of initial data.

The peripheral work module is responsible for: work with sensors, which consists in periodically reading data from sensors; work with the system timer, which consists in setting the initial time and periodically reading the current time of day; work with actuators, which consists in transmitting control signals to relays to change the state of the actuators.

The neural network-based data processing module is responsible for: neural network initialization, which consists in loading the neural network dimension, the type of neuron functions, and matrices with weighting coefficients; entering input data into the neural network; neural network simulation; output of output data for the formation of control commands for controlling actuators.

The main task of this module is to simulate the work of a neural network. For this purpose, a subprogram has been implemented that performs successive calculations of the value of each of the neurons, taking into account the type of function of the neuron and the connections between neurons. At the end of the subprogram, the value of each of the elements is formed.

The main feature of the neuro-controller is its cyclical operation. Since there is no need to frequently poll and update the system state, the interrupt operator is used, which stops the main cycle of program execution and limits the frequency of execution of the main cycle.

During the execution of the main cycle, a subroutine is called to simulate the operation of the neural network. Based on its response, commands are formed to control the actuators.

The algorithm of the subprogram operation for simulating the operation of the neural network is presented in Fig. 12.

**Figure 12. Block diagram of the algorithm of the subprogram for simulating the operation of the neural network**

The subprogram is responsible for calculating the values of each of the system's neurons. As input data, the subprogram receives measured values from sensors and the system timer. As output data, the subprogram outputs the value of the state to which each of the actuators should be transferred (on/off).

## CONCLUSIONS

The structure of the basic neuro-controller for the processing of technological data for the energy efficiency management system of the enterprise has been developed. It is based on the modular principle, which makes it possible to quickly modernize the technical system.

A model for processing fuzzy and unstructured data for an intelligent mini-greenhouse based on an artificial neural network has been developed. It was conducted the training of artificial neural network and the error checking of the model, which does not exceed 2%.

The software and hardware of the neuro-controller for the intelligent mini-greenhouse was developed. The hardware is based on the STM32 microcontroller, which provides high mass and size indicators of the device. The software for setting up the neural network is implemented in Java, and the system software of the microcontroller is implemented by standard development tools.

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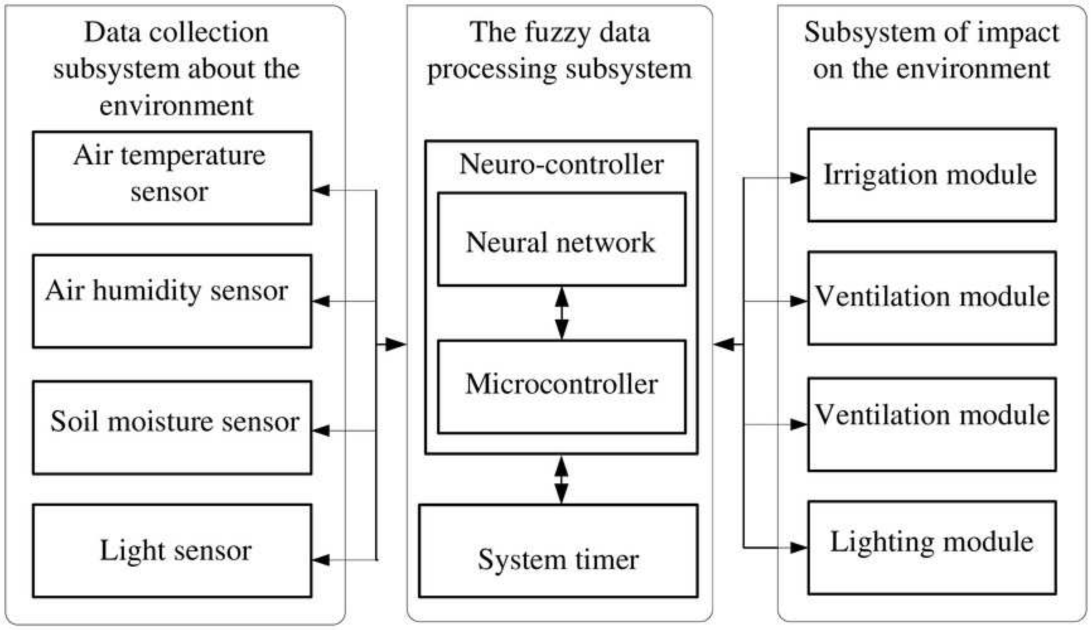
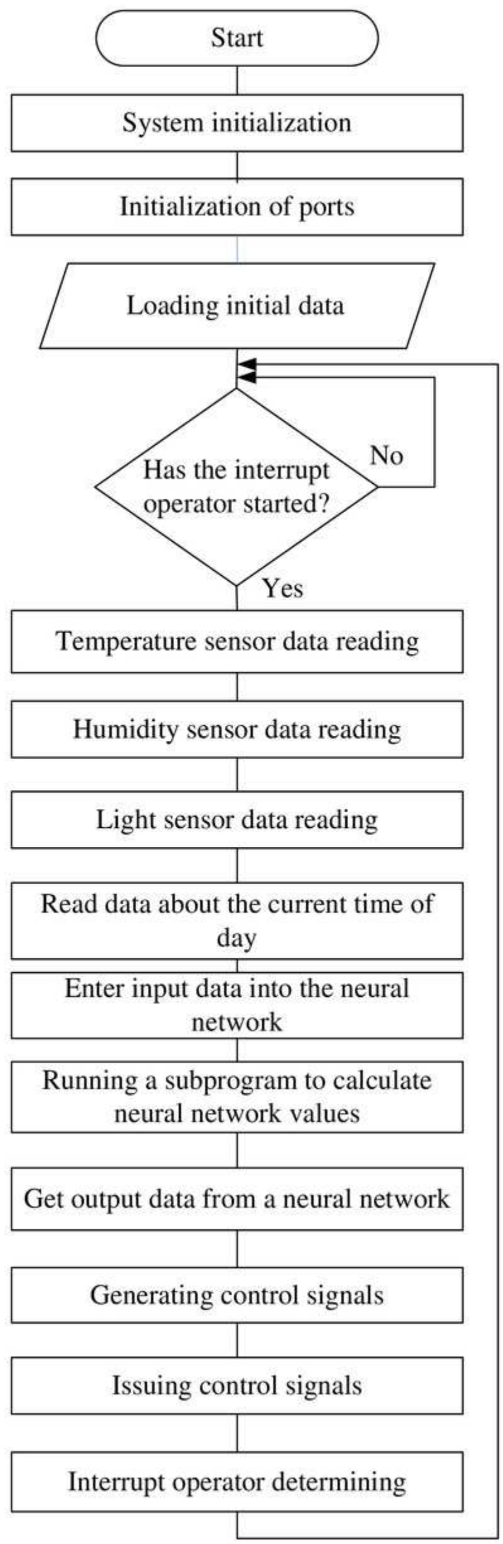
# Figure 1

Structure of the control subsystem of intelligent mini-greenhouse


Data collection subsystem about the environment
Air temperature sensor
Air humidity sensor
Soil moisture sensor
Light sensor
The fuzzy data processing subsystem
Neuro-controller
Neural network
Microcontroller
System timer
Subsystem of impact on the environment
Irrigation module
Ventilation module
Ventilation module
Lighting module

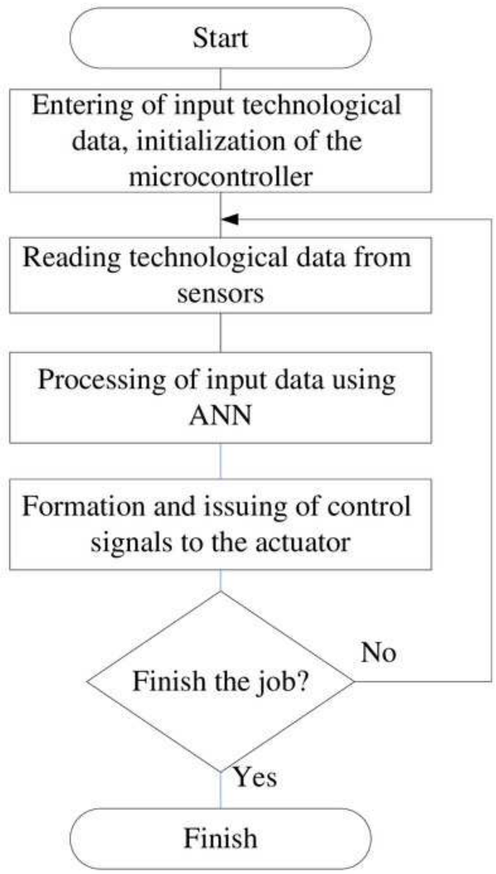
# Figure 2

Block diagram of the neuro-controller algorithm for controlling an intelligent mini-greenhouse


Start
System initialization
Initialization of ports
Loading initial data
Has the interrupt operator started?
No
Yes
Temperature sensor data reading
Humidity sensor data reading
Light sensor data reading
Read data about the current time of day
Enter input data into the neural network
Running a subprogram to calculate neural network values
Get output data from a neural network
Generating control signals
Issuing control signals
Interrupt operator determining

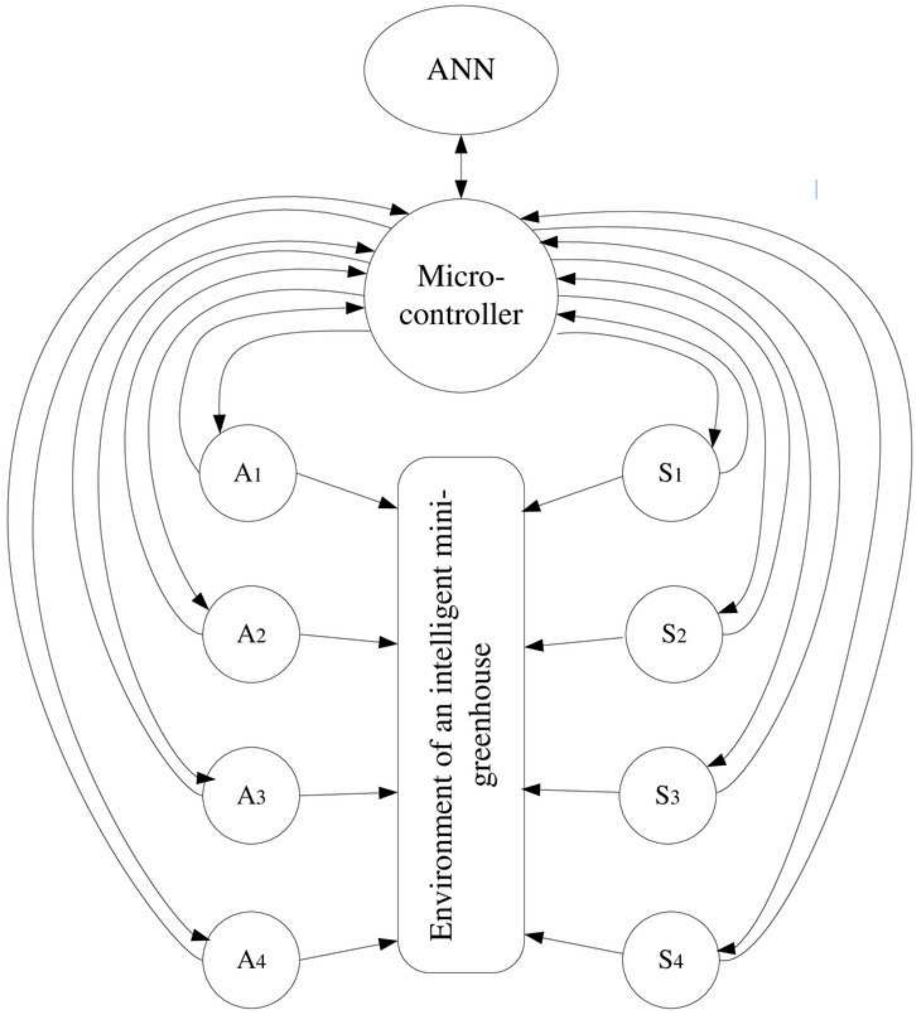
# Figure 3

A simplified block diagram of algorithm of neuro-controller operation


Start
Entering of input technological data, initialization of the microcontroller
Reading technological data from sensors
Processing of input data using ANN
Formation and issuing of control signals to the actuator
Finish the job?
No
Yes
Finish

# Figure 4

Structural model of the intelligent mini-greenhouse control system in the graph form


ANN
Micro-
controller
A1
A2
A3
A4
S1
S2
S3
S4
Environment of an intelligent mini-
greenhouse

# Figure 5

An example of the main class code for data normalization

```
public class Main {
public static void main(String[] args) {
// TODO Auto-generated method stub
GHDataBank bank = new GHDataBank();
List<GHNormalizedState> normalizedData = GHDataNormalizer.normalize(bank.getStates());
printNormalizedDataSet(normalizedData);
}
private static void printNormalizedDataSet(List<GHNormalizedState> normalizedData) {
StringBuilder builder = new StringBuilder();
for(GHNormalizedState state : normalizedData) {
builder.append("\n");
int length = state.getData().length;
for(int i = 0; i < length; i++) {
builder.append(state.getData()[i]);
if(i < length -1) {
builder.append("\t");
}
}
}
System.out.println(builder.toString());
} }
```

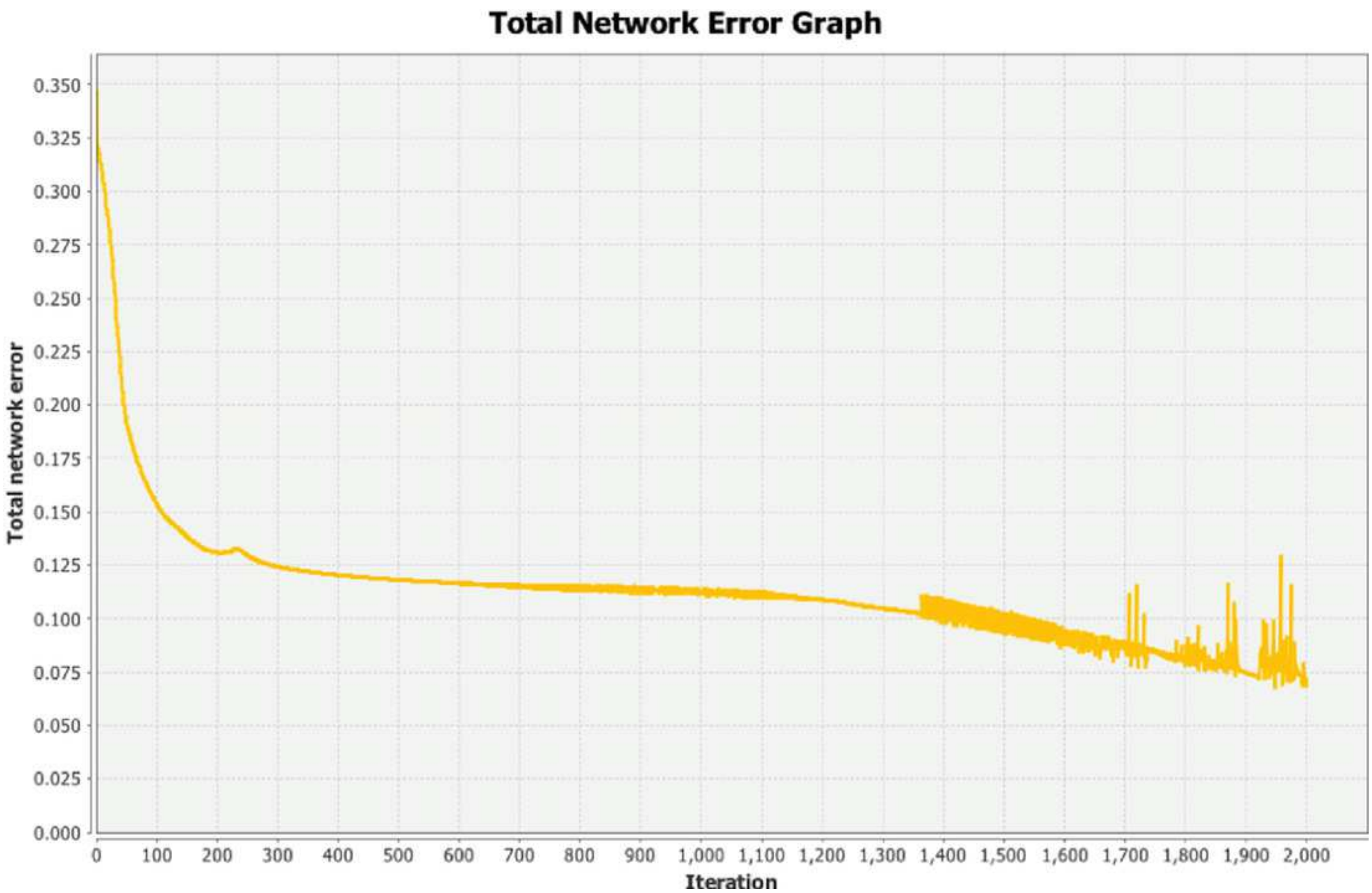
# Figure 6

A fragment of the training sample

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 0.13659352 | 0.5035774 | 0.01 | 6.49417 | 0.0 | 0.0 | 1.0 | 0.0 |
| 0.11472501 | 0.47745776 | 0.01 | 0.27352238 | 0.0 | 0.0 | 1.0 | 0.0 |
| 0.1738139 | 0.7501913 | 0.0 | 0.7836361 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.17271096 | 0.016949594 | 0.01 | 6.690731 | 0.0 | 0.0 | 1.0 | 1.0 |
| 0.1981485 | 0.69929206 | 0.01 | 7.609274 | 0.0 | 0.0 | 1.0 | 0.0 |
| 0.109491974 | 0.40013844 | 0.01 | 3.1834803 | 0.0 | 1.0 | 1.0 | 0.0 |
| 0.12645467 | 0.8741783 | 0.0 | 10.257828 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.098818235 | 0.98171824 | 0.0 | 0.45594692 | 0.0 | 1.0 | 0.0 | 0.0 |
| 0.16916224 | 0.31850475 | 0.01 | 6.956049 | 0.0 | 0.0 | 1.0 | 1.0 |

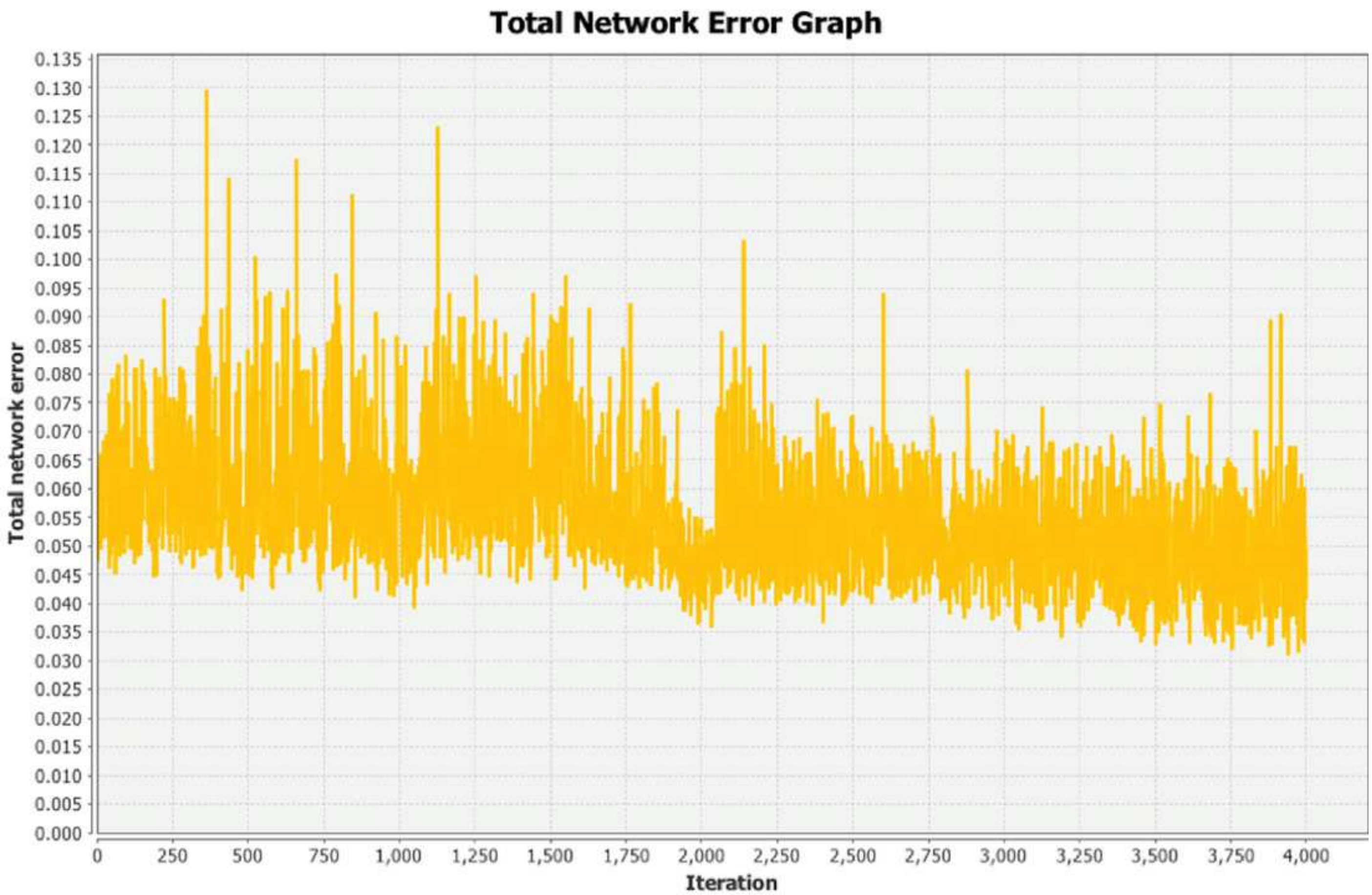
# Figure 7

*Results of neural network training, iterations 1-2000*



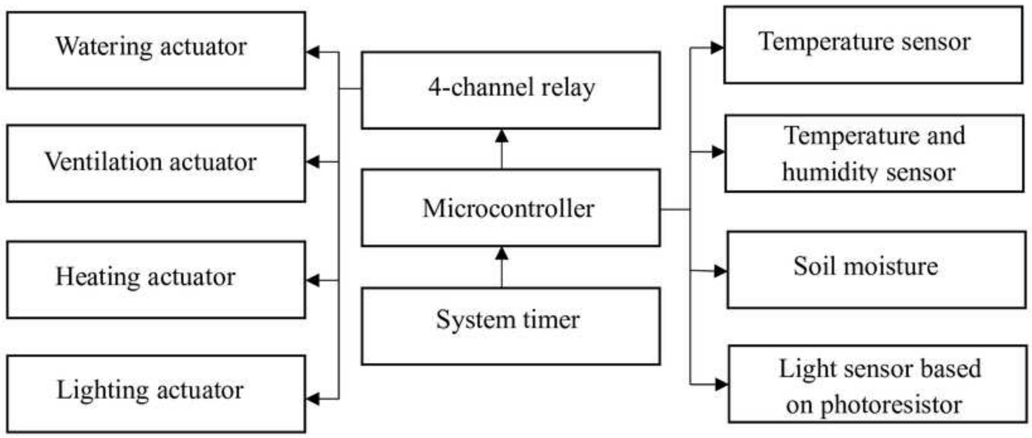
# Figure 8

*Results of neural network training, iterations 2001-6000*



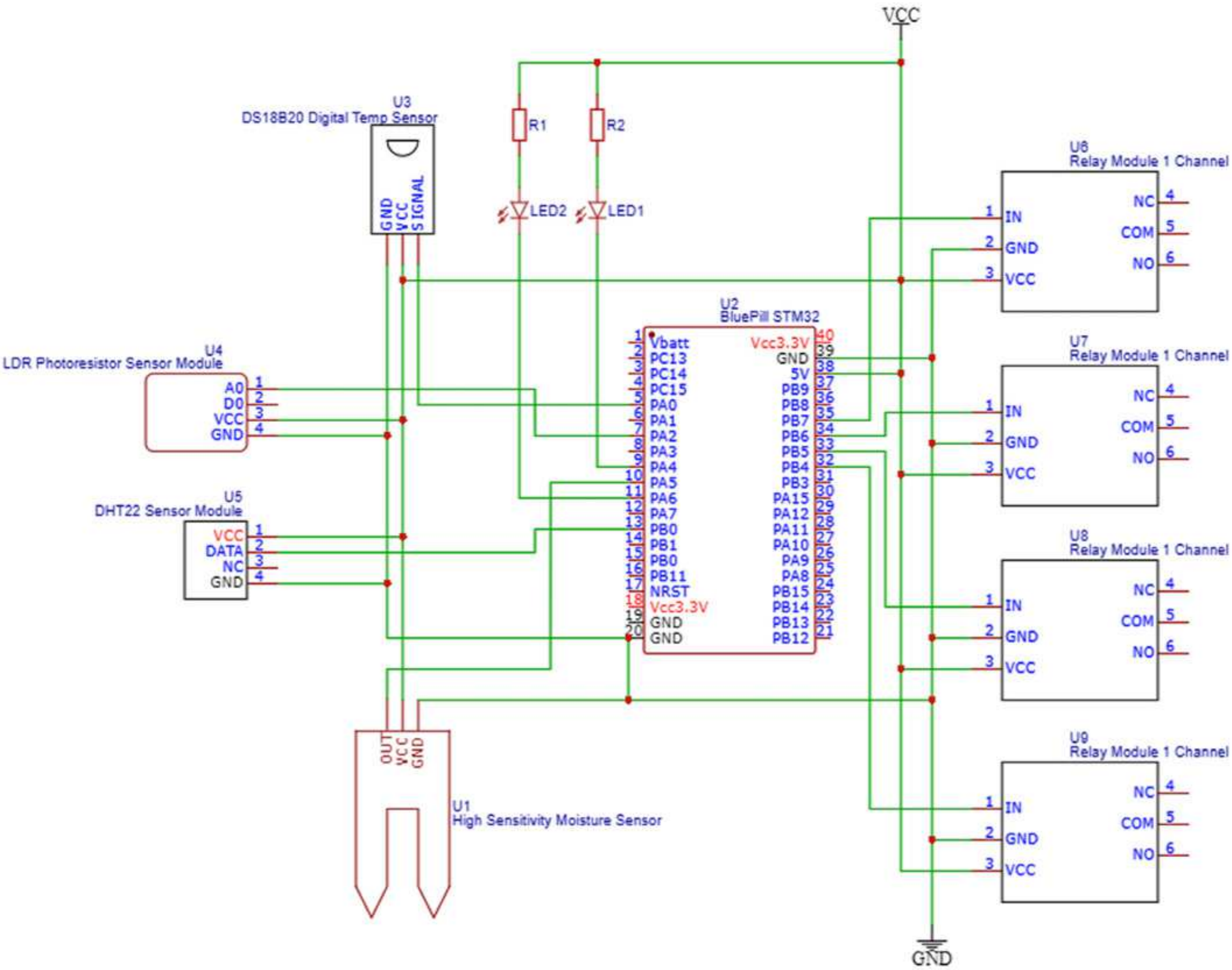
# Figure 9

Structural diagram of the hardware of the intelligent mini-greenhouse control system


Watering actuator
Ventilation actuator
Heating actuator
Lighting actuator
4-channel relay
Microcontroller
System timer
Temperature sensor
Temperature and humidity sensor
Soil moisture
Light sensor based on photoresistor

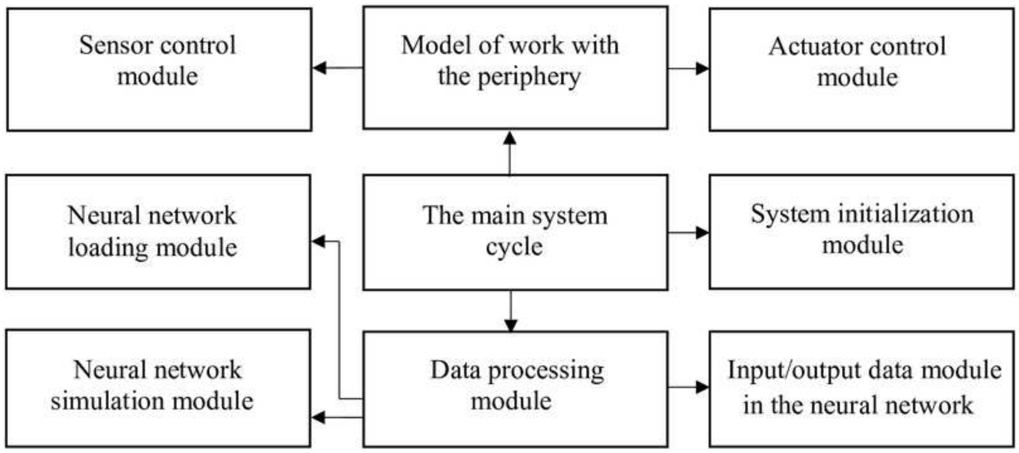
# Figure 10

*Scheme of the hardware implementation of the neuro-controller*



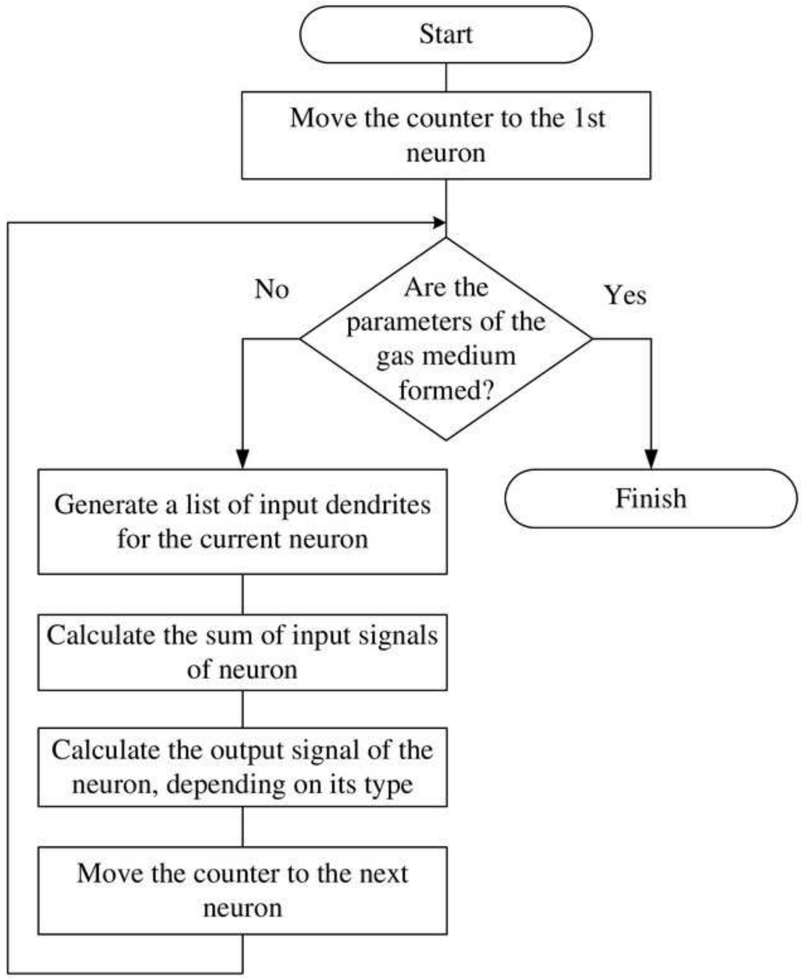
# Figure 11

Software structure of the intelligent mini-greenhouse management system


Sensor control module
Model of work with the periphery
Actuator control module
Neural network loading module
The main system cycle
System initialization module
Neural network simulation module
Data processing module
Input/output data module in the neural network

# Figure 12

Block diagram of the algorithm of the subprogram for simulating the operation of the neural network


Start
Move the counter to the 1st neuron
No
Are the parameters of the gas medium formed?
Yes
Generate a list of input dendrites for the current neuron
Finish
Calculate the sum of input signals of neuron
Calculate the output signal of the neuron, depending on its type
Move the counter to the next neuron

## Table 1(on next page)

Work scenarios of intellectual greenhouse

| **Meaning of conditions** | **Action** |
|---|---|
| High air temperature | Turn on the fan<br>turn off the heater |
| Low air temperature | Turn on the heater<br>turn off the fan |
| High air humidity | Turn on the fan |
| Low air humidity | |
| High soil moisture | Turn off watering |
| Low soil moisture | Turn on watering |
| High level of outdoor lighting | |
| Low level of external lighting and time for active lighting of plants | Turn on the external lighting |
| Outside the time area for active lighting | Turn off the external lighting |

1