Development of an Intelligent System with Fuzzy Logic for Indoor Microclimate Control

Kateryna Yalova[1,†], Mykhailo Babenko[1,†], Yurii Babenko[2,*,†], Kyrylo Krasnikov[1,†] and Viktor Bagriy[1,†]

[1]*Dniprovsky State Technical University, Dniprobydivska Street 2, Kamianske, 51918, Ukraine*
[2]*Taras Shevchenko National University of Kyiv, Volodymyrska Street 64/13, Kyiv, 01601, Ukraine*

Abstract
The paper presents the results of modeling a fuzzy logic controller for an intelligent system for monitoring and managing indoor microclimate conditions. The use of fuzzy logic in programming provides certain advantages, such as simplicity of data input into the control system and the ability to reduce errors inherent in classical microcontrollers. The microprocessor system used is based on the Arduino UNO board model Arduino Rev3, which features the ATMEL ATmega328P microcontroller and is compact, cost-effective, and easy to use. A fuzzy logic controller is utilized in the system for effective microclimate regulation. During the development of the intelligent system, the LabView software environment and Arduino IDE were employed. The study breaks down the system into several components and establishes links between them to enhance the efficiency of the software. Decision-making is determined by the system's functional requirements and the selected equipment for implementation.

Keywords
intelligent system, microclimate control, microcontroller, Arduino IDE, LabView

1. Introduction

In any indoor space, a unique microclimate is formed—a combination of factors that affect comfort and well-being during occupancy [1]. The main characteristics of the microclimate include: temperature, relative humidity, air quality, air movement speed, thermal (infrared) radiation intensity, carbon dioxide concentration, fresh air intake, dust levels, etc. [2]. The values of microclimate parameters are classified as:

- Optimal: These include indicators of a person’s functional state, optimal thermal influence, minimal thermoregulation strain, and a sense of comfort.
- Permissible: These represent criteria where a person may experience discomfort, applied when optimal standards cannot be met.

For each type of space, sanitary norms and standards are established to regulate permissible microclimate characteristics to ensure optimal living and working conditions. In Ukraine, the main regulatory document governing microclimate parameters in industrial premises is DSN 3.3.6.042-99 "Sanitary Norms for the Microclimate of Industrial Premises", which specifies optimal and permissible microclimate indicators and sets requirements for measurement methods.

Information Technology and Implementation (IT&I-2024), November 20-21, 2024, Kyiv, Ukraine
*Corresponding author.
†These authors contributed equally.
yalovakateryna@gmail.com (K. Yalova); mvbab130973@gmail.com(M. Babenko); yurii.babenko@knu.ua (Y. Babenko); kir_kras@ukr.net (K. Krasnikov); vvbagry@ukr.net (V. Bagriy)
0000-0002-2687-5863 (K. Yalova); 0000-0003-1013-9383 (M. Babenko); 0000-0002-8115-3329 (Y. Babenko); 0000-0002-4241-0572 (K. Krasnikov); 0000-0001-8817-9217 (V. Bagriy)

Microclimate regulation methods are categorized as passive or active [3]. Passive methods involve architectural and design solutions that naturally regulate microclimate parameters, such as natural ventilation, sun protection designs, or insulation. Active methods involve the use of devices, systems, and technologies to control microclimate parameters actively. These methods have evolved significantly, from basic heating systems and mechanical ventilation to sophisticated intelligent automated systems utilizing fuzzy logic and machine learning.

The task of developing new climate control systems and improving existing ones remains a relevant scientific and practical challenge, as effective management of microclimate parameters ensures a high level of comfort for occupants and energy efficiency in buildings [4]. The application of fuzzy logic provides flexible and smooth control of microclimate parameters, allowing the use of fuzzy verbal categories and adaptive solutions. This improves the efficiency of climate control systems, as fuzzy logic accounts for a wide range of factors and parameters under conditions of incomplete or inaccurate information. Consequently, this positively affects the performance of microclimate control systems, creating an optimally comfortable environment with minimal energy consumption, which is critically important in the context of current energy efficiency and sustainable development requirements.

The goal of this study is to develop hardware, algorithmic, and software components for an indoor microclimate control system. The research tasks include: developing a fuzzy logic controller for the system, creating a system operation algorithm, implementing the hardware component, and designing the system's software architecture. The advantages of using fuzzy logic in the developed system include the ability to adjust the system's actions in real time based on current microclimate parameters and considering individual user preferences. The practical significance of the proposed solutions lies in the compactness, low cost, and ease of use of the developed intelligent system.

2. Related Works

Numerous studies have substantiated [1-6] that the state of the microclimate significantly affects people's health, work capacity, and resistance to diseases. Effective control of the microclimate helps reduce health risks and increases overall comfort and subjective satisfaction, which has a significant impact on cognitive functions, especially in workplaces and educational institutions. The studies in [3, 7-9] present findings on the impact of microclimate quality on people's productivity and work performance, emphasizing the importance of ventilation and control of indoor microclimate as a whole.

Currently, microprocessor-based systems for indoor climate control are used to monitor and automatically regulate microclimate parameters [10-11]. The most advanced systems are smart HVAC (heating, ventilation, and air conditioning) systems that use machine learning algorithms combined with Internet of Things (IoT) technologies. The use of automated indoor climate control systems has dual benefits: positively impacting health, well-being, and productivity, while optimizing microclimate parameters for rational energy consumption [12]. Another line of research focuses on the influence of indoor microclimate parameters on energy efficiency, highlighting microclimate control as a critical factor for rational energy use [10].

Advances in computer technology and electronics have enabled the development of climate control systems that process sensor data in real time and send commands to regulate devices, such as thermostats or air conditioners. Achievements in machine learning have allowed the integration of prediction modules into microclimate control systems [12-14]. These prediction modules anticipate changes in microclimate parameters based on intelligent processing of retrospective data and/or weather forecasts.

In cases where microclimate parameters are challenging to predict due to their nonlinear nature, fuzzy logic can lead to more effective decision-making, ultimately improving comfort, energy efficiency, and adaptability of climate control systems. A popular and practically valuable approach is the use of fuzzy logic to create linguistic variables and rules in microclimate control systems. The works in [15-18] describe the design and successful implementation of this approach. The application of fuzzy logic improves the quality of microclimate parameter management compared to binary systems or rigid rule-based controllers, as it allows for processing imprecise input values and converting them into specific commands for electronic devices.

3. Proposed methodology

3.1. Development of a Fuzzy Logic Controller

The modern smart home is a dynamic ecosystem where various devices work together to maintain an optimal living environment [15]. To achieve this, we will develop control system. The fuzzy logic controller (FLC) is well-suited for applications requiring a degree of uncertainty, or imprecision, like home environmental control. Unlike traditional binary logic, where an input either belongs to a set or it doesn't, fuzzy logic allows inputs to belong to multiple sets with varying degrees of membership [16].

The construction of control systems using a fuzzy logic controller was carried out in the following order:

- selecting inputs and outputs of the control system.
- defining membership functions for each input and output variable.
- forming a database of fuzzy rules.
- selecting and implementing a fuzzy inference algorithm.
- analyzing the control process using the developed system.

The design of the fuzzy logic system was performed using the Fuzzy System Designer add-on of the LabView software environment. Experiments were conducted using software developed by the authors that implements the fuzzy system, and were compared with results obtained in the LabView environment.

We start with the primary input parameters which are temperature (0–50°C), CO_2 concentration (0–1000 ppm), and humidity (0–100%). The system provides control over the smart house humidifier (on/off), conditioner (on/off), and the state of the heater-cooler (freeze/off/warm). The system monitors indoor temperature, ranging between different conditions from freezing to very warm environments. CO_2 levels are important for assessing air quality, and the system measures concentrations between 0 and 1000 parts per million (ppm). High CO_2 levels indicate poor air circulation, potentially necessitating adjustments in the ventilation or conditioning system. Relative humidity, measured on a scale from 0% to 100%, is influences comfort, like preventing dry air.

The controller influences three major output controllables. The first one is humidifier on/off: The system turns the humidifier on or off based on the humidity level and overall environmental conditions. The air conditioner can be turned on or off depending on the temperature and CO_2 levels. The heater/cooler operates in freeze state when the system cools down the environment. It is off when neither heating nor cooling is activated. It can warm up to increases the temperature to reach comfort levels.

Each input parameter (temperature, CO_2, humidity) is characterized by fuzzy sets.

For the given task, comfortable conditions are determined primarily by the humidity and temperature of the indoor air. Measurements of these parameters are fed to the inputs of the control system. The output signals of the system are on and off signals that are sent to the heater, air conditioner, and humidifier. For the fuzzy temperature controller, the input linguistic variable is the room temperature. According to recommendations, the indoor air temperature should be between 18 and 24 °C. If the temperature in the room is below 18 °C, it is considered low and has a low level of comfort for people. If the air temperature is above 24 °C, it is considered overheating. Thus, this input variable has three terms (low, normal, high). The output signals are the on and off signals for the heater and air conditioner operating in cooling mode, so these signals have two terms each (On and Off). The definition of the membership functions was performed in Fuzzy System Designer. The results obtained for the input and two output variables are shown in Figure 1.

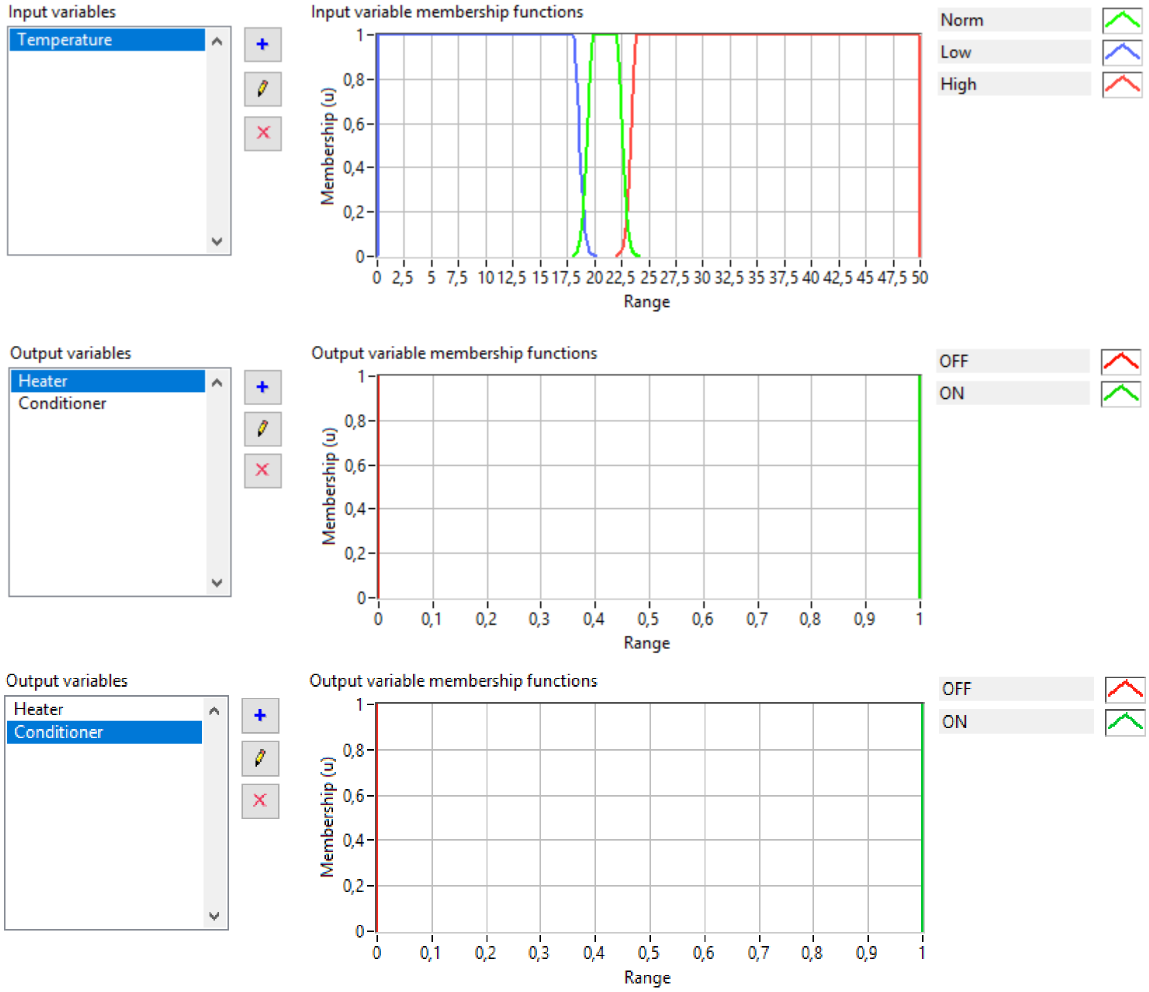


Figure 1: Membership functions for the input and two output variables of the fuzzy temperature controller

Fuzzy set of temperature is following:

(Temperature, T={Low, Norm, High}, X=[0 .. 50])

μ_{Low} = trapmf (0,0,18,21), μ_{Norm} = trapmf (18,20,22,24), μ_{High} = trapmf (21,24,50,50).

Fuzzy rules combine the fuzzy sets of the input parameters to determine the appropriate output actions:

IF Thermometer is Norm THEN Heater is Off ALSO Conditioner is Off

IF Thermometer is High THEN Heater is Off ALSO Conditioner is On

IF Temperature is Low THEN Heater is On ALSO Conditioner is Off

In this software environment, it is possible to test the developed fuzzy logic controller (Figure 2).

The test results confirm the correctness of the adopted decisions. The fuzzy temperature controller has one input and two outputs; thus it has a SIMO structure.

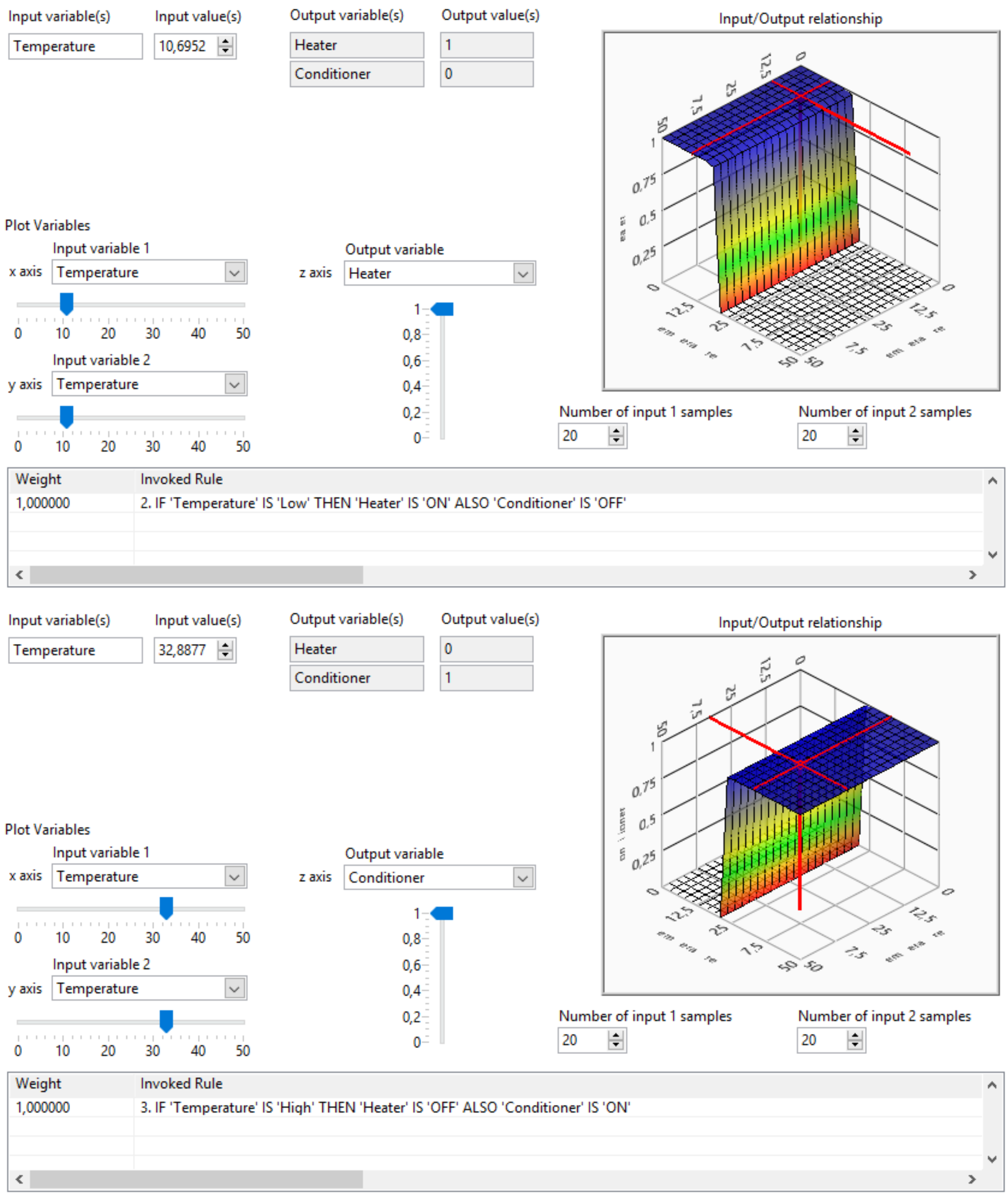


Figure 2: Test results of the fuzzy temperature controller

For the fuzzy humidity controller, the input linguistic variable is the indoor air humidity. The output linguistic variable is the control signal value sent to the humidifier.

Normal air humidity ranges between 40-60%, high humidity exceeds 60%, and dry air has humidity below 40%. The membership function for the input variable also has three terms: low, normal, high (Figure 3). The membership function for the output variable has two terms (On and Off).

Fuzzy set of Humidity is following:

(Humidity, H={Low, Norm, High}, X=[0 .. 100])

μ_{Low} = trapmf (0,0,40,48), μ_{Norm} = trapmf (38,48,53,62), μ_{High} = trapmf (53,60,100,100).

The obtained fuzzy rule base contains three rules:

IF Humidity is High THEN Humidifer is Off

IF Humidity is Low THEN Humidifer is On

IF Humidity is Norm THEN Humidifer is Off

The test results confirm the correctness of the adopted decisions (Figure 4).

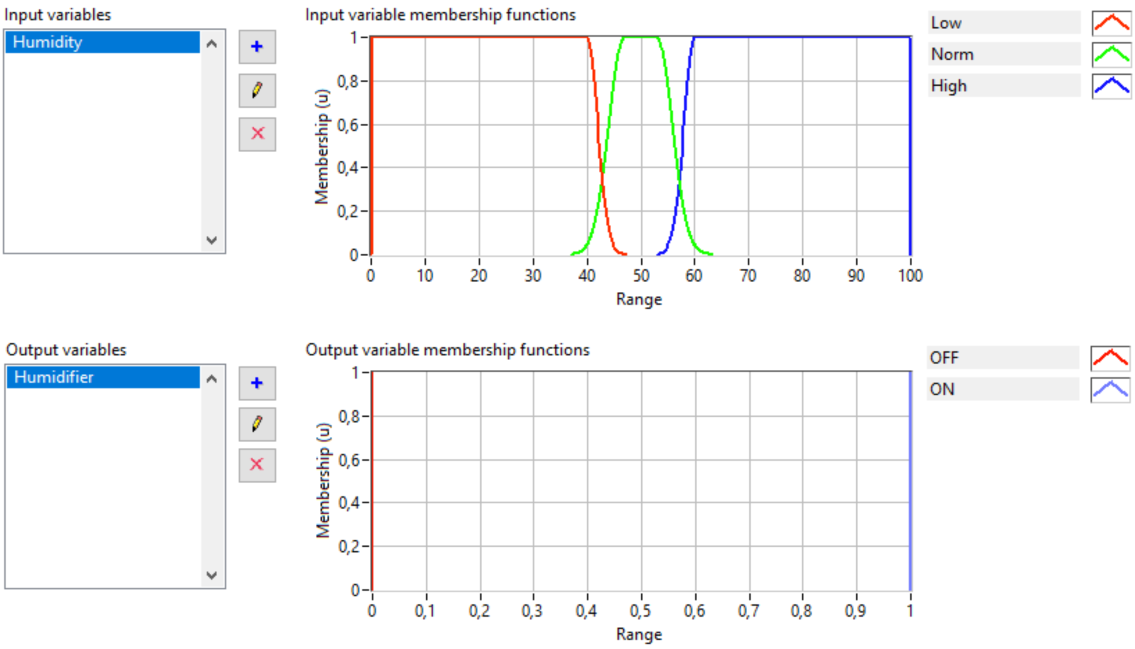


Figure 3: Membership functions for the input and output variables of the fuzzy humidity controller

3.2. Mathematical Description of Fuzzy Controller

Control signal u can be represented by formula:

$$u = defuzz\left(\bigcup_{i=1}^{n}\left(\mu_{A_u}(x_i)\right)\right).$$

where xi – input variable.

For the temperature input variable T, let's define the following triangular membership functions:

$$\mu_{T_{Low}}(T) = max\left(min\left(1, \frac{21-T}{3}\right), 0\right),$$

$$\mu_{T_{Norm}}(T) = max\left(min\left(\frac{T-18}{2}, 1, \frac{24-T}{2}\right), 0\right),$$

$$\mu_{T_{High}}(T) = max\left(min\left(\frac{T-21}{3}, 1\right), 0\right).$$

For the humidity input variable H the following triangular membership functions are defined:

$$\mu_{H_{Low}}(H) = max\left(min\left(1, \frac{48-H}{8}\right), 0\right),$$

$$\mu_{H_{Norm}}(H) = max\left(min\left(\frac{H-38}{10}, 1, \frac{62-H}{9}\right), 0\right),$$

$$\mu_{H_{High}}(H) = max\left(min\left(\frac{H-53}{7}, 1\right), 0\right).$$

To determine the fuzzy output the fuzzy inference is used:

$$\mu_{output}(u) = min\left(\mu_{T_{Low}}, \mu_{H_{High}}\right).$$

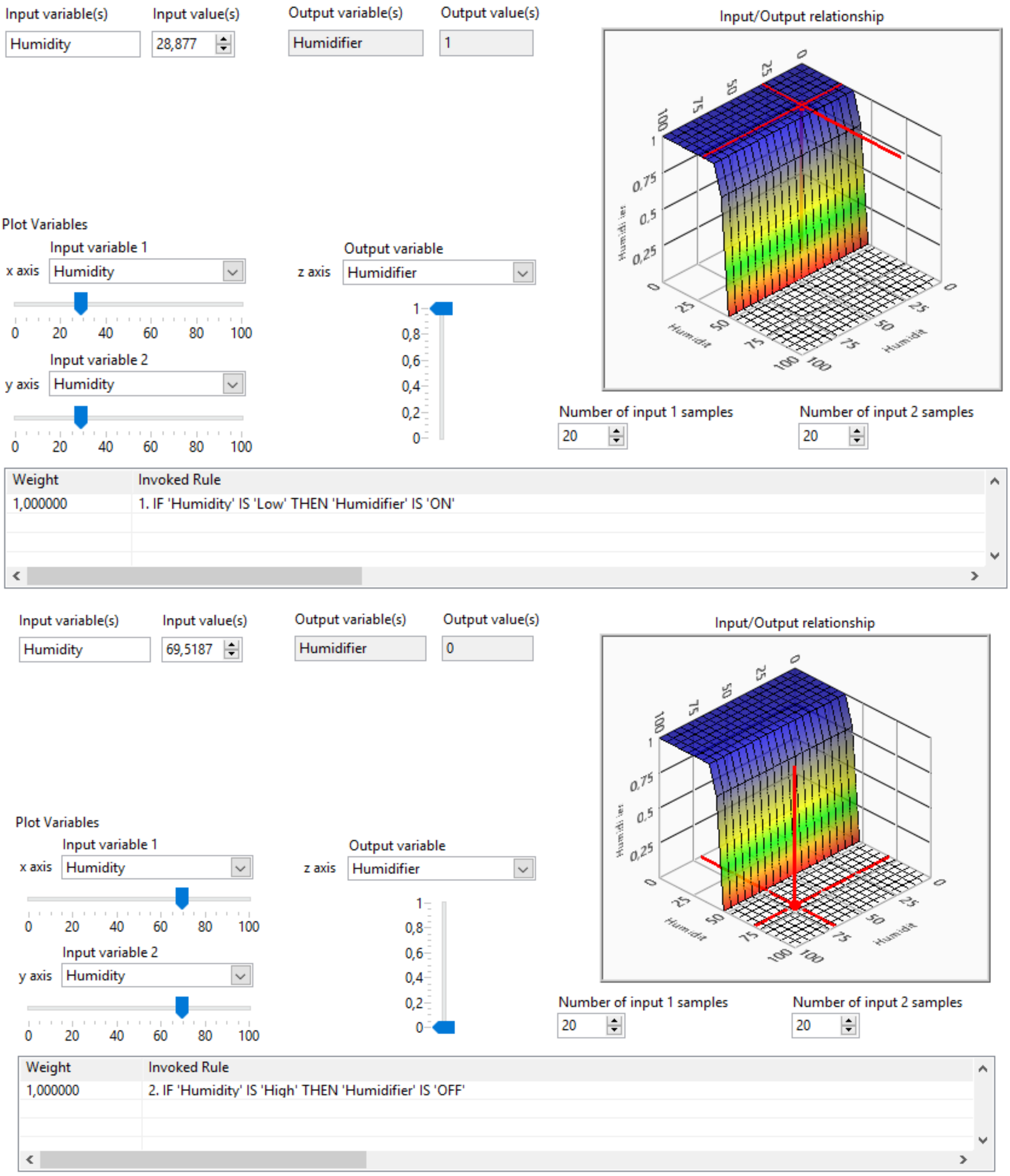


Figure 4: Test results of the fuzzy humidity controller

3.3. Development of Algorithmic and Software

The process of converting exact inputs (such as 27°C temperature or 650 ppm CO_2) into fuzzy values is done using fuzzification. After applying the fuzzy rules, the resulting fuzzy output converted back into an exact action, such as turning on the air conditioner or activating the humidifier. The popular method of defuzzification is centroid method, which calculates the center of the area under the membership function curve.

The FLC operates within a feedback control system. Sensors continuously monitor the environmental parameters (temperature, humidity, CO_2), sending real-time data to the controller. The FLC then processes this data, applies the fuzzy logic rules, and adjusts the operation of the humidifier, air conditioner, and heater-cooler.

The developed flowchart of the system's operation algorithm is shown in Figure 5.

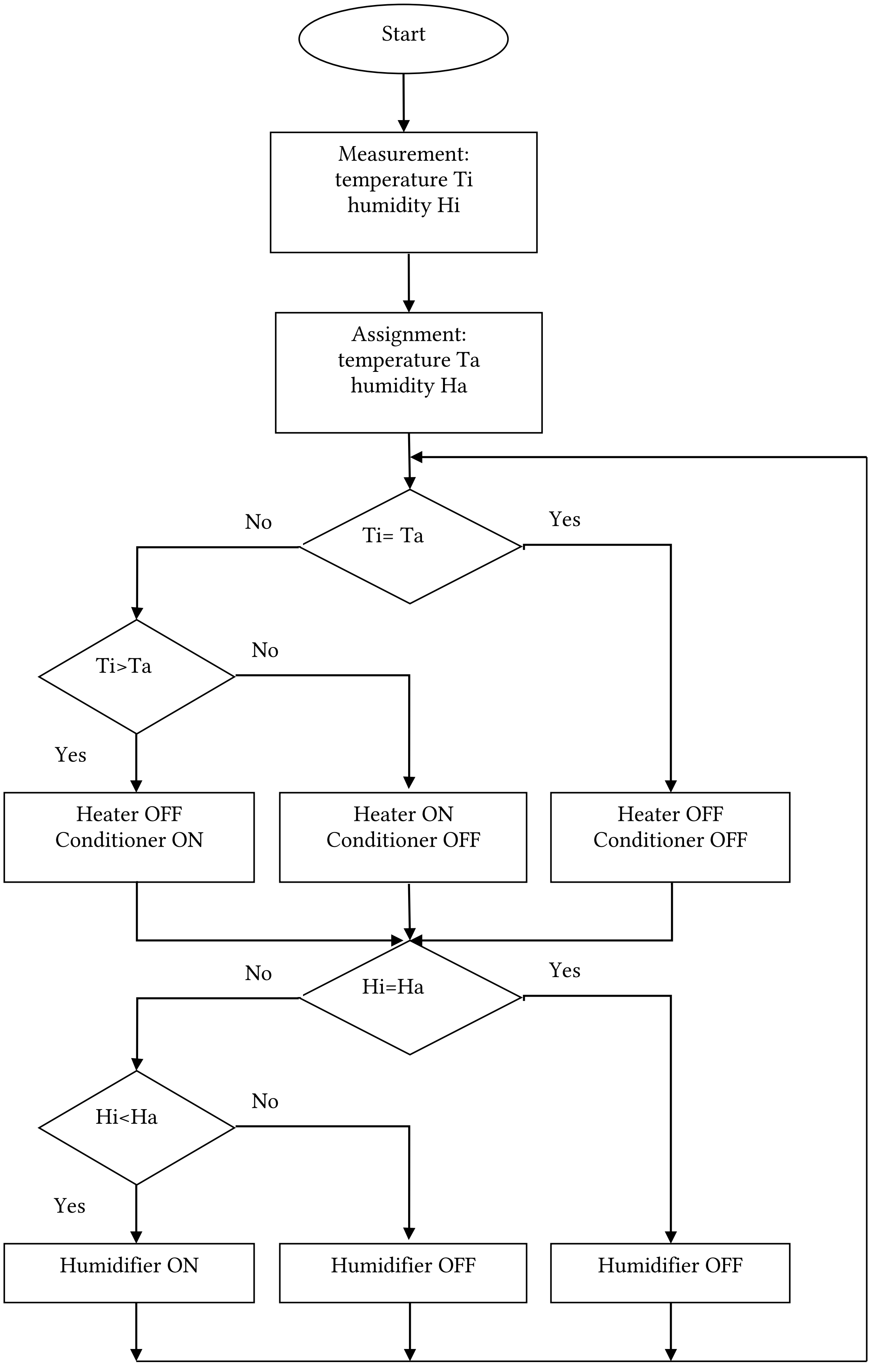


Figure 5: Flowchart of the control algorithm for the indoor climate control system

The system architecture involves three layers. The input layer collects data from sensors (temperature, CO_2, humidity). The processing layer applies fuzzification, evaluates fuzzy rules, and defuzzifies outputs. The output layer sends control signals to the smart house devices.

Through the application of fuzzy rules and logic, this system can manage the balance between comfort, air quality, and energy consumption, providing a seamless experience for smart home users.

The requirements for the functioning of this system are reduced to ensuring the specified temperature and humidity conditions in the room. To meet these requirements, the system collects temperature and humidity measurements from the room and sends the measurement results to the microcontroller.

The main criteria for software development are execution speed, ease of use, cross-platform capability, simplicity of implementation, and many others [14]. In this case, the project is implemented using an Arduino UNO board, model Arduino Rev3, based on the ATMEL ATmega328P microcontroller. The Arduino hardware board consists not only of the microcontroller but also includes everything necessary to connect to external peripheral devices. In addition, it has a built-in programmer that allows direct programming from a computer. A distinctive feature of these microprocessor devices is the availability of open-source code and a significant number of libraries for the interaction of the embedded microcontroller with other external components. It is widely used for developing interactive objects and receiving data from various sensors or switches. Considering this, Arduino is the most popular embedded platform used in many projects.

The code is developed in the native Arduino IDE, based on a programming language that is a variant of C/C++ for microcontrollers. Arduino projects can be either autonomous or interact with any software running on a computer. In this project, LabView software with a visual graphical programming language was used.

The general view of the front panel and the block diagram of the developed system project are shown in Figures 6 and 7, respectively.

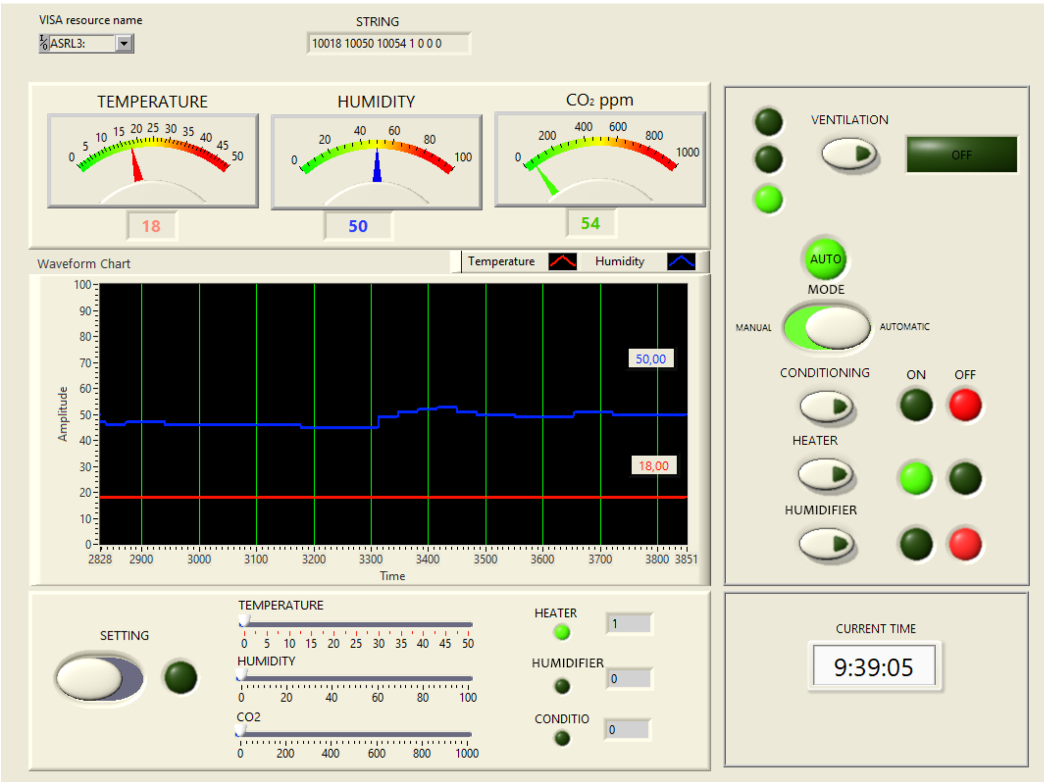


Figure 6: Front panel of the indoor climate control system

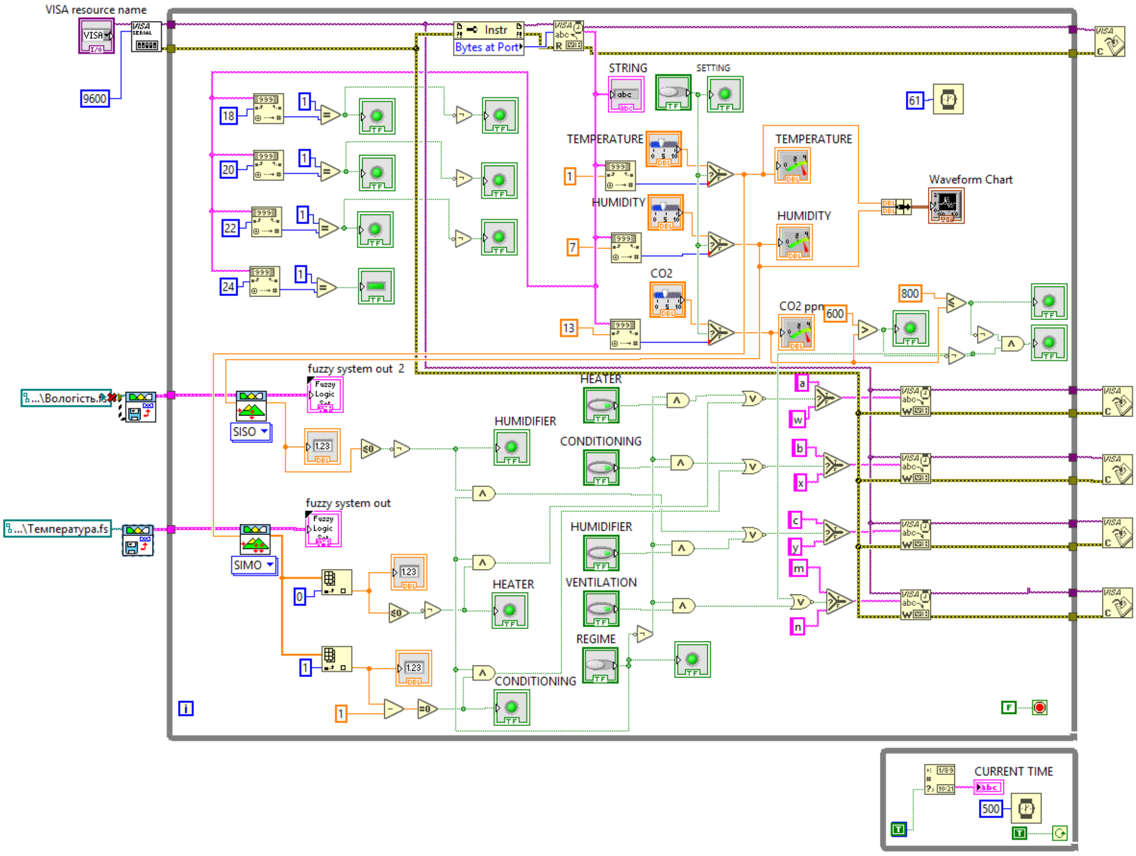


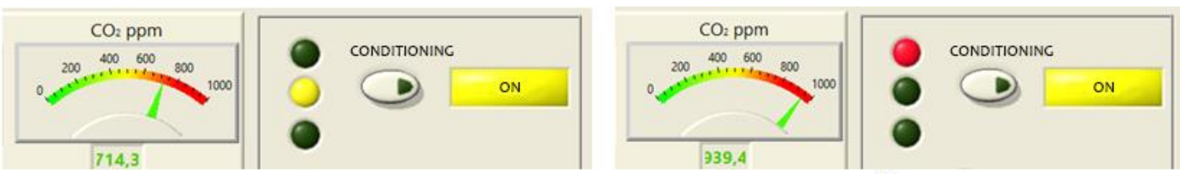
Figure 7: Block diagram of the indoor climate control system

The front panel displays current measurements of temperature, humidity, and CO_2 concentration in real time. Changes in temperature and humidity can be monitored graphically.

The air in the room should have a CO_2 concentration between 0.01-0.05%. An elevated CO_2 level ranges from 0.05-0.09%, while a high concentration exceeds 0.09%. If the indoor climate control system detects elevated or high CO_2 levels, the exhaust ventilation is activated. In this case, the front panel displays a warning and a danger signal (Figure 8).

The developed system can operate in both automatic and manual modes. Switching between modes is done using an interactive switch on the front panel. In manual mode, the user turns the actuators—heater, air conditioner, humidifier, and ventilation—on or off (Figure 9). In automatic mode, these operations are performed by the system based on the built-in regulator.

The developed microprocessor system also has a configuration mode, which is activated using an interactive switch on the front panel (Figure 10). In this mode, sensor signals are disconnected from the system inputs and replaced by signals from simulators. The values of the simulated signals can be changed from the front panel. This solution allows modeling of any possible situation at the site and evaluating the system's response, as well as checking and adjusting the regulators.



a *b*

Figure 8: Identification of elevated (a) and high (b) CO_2 concentration levels in indoor air

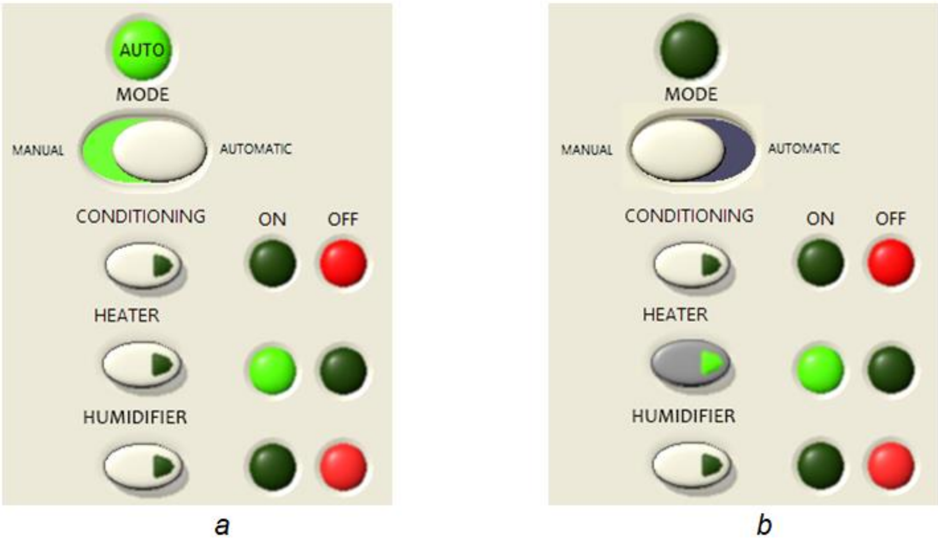


Figure 9: System operating modes: automatic (a) and manual (b)

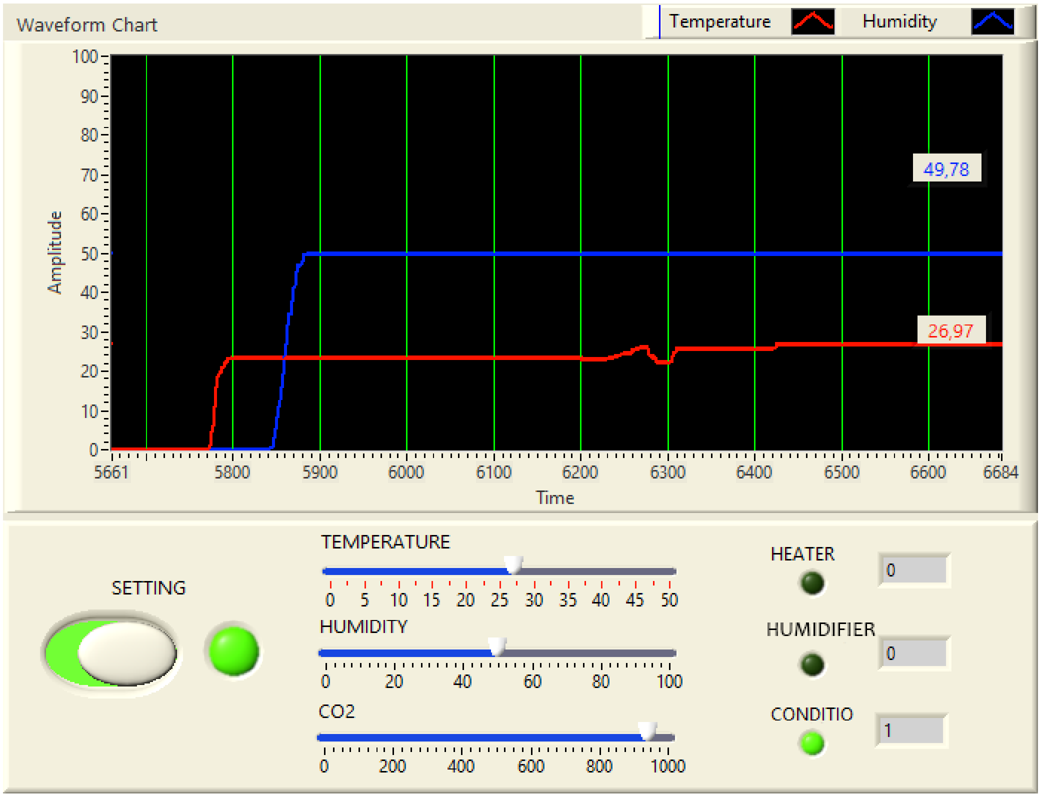


Figure 10: System configuration mode

4. Results

A simulation of fuzzy logic controllers was conducted for the developed intelligent indoor climate control system. The results highlighted several advantages of this development, including:

- Enhanced quality of control.
- Low sensitivity to changes in the parameters of the controlled object.
- Simplified synthesis of control systems with fuzzy logic using modern hardware and software support compared to traditional control systems.

The simulation was carried out using LabVIEW—a platform and development environment for the visual graphical programming language by National Instruments (USA). Integrating the Arduino platform with this environment provides many opportunities to simplify project implementation:

- A user-friendly package allows lines of code to be converted into a graphical program, hiding the complexities of hardware and software.
- The data flow programming model focuses on code implementation by connecting the inputs and outputs of graphical blocks, enabling an intuitive graphical code approach instead of textual programming.
- It allows for quick and easy creation of a graphical user interface for the developed program.
- LabVIEW software includes a wide range of useful add-ons and libraries, opening new possibilities for project implementation.

5. Conclusions

An intelligent indoor climate control and management system based on fuzzy control has been developed. The integration of the Arduino platform with the LabView programming environment significantly reduces development time and enhances system performance. Software testing has been conducted, demonstrating that the developed software meets the requirements of the technical specifications. A comparison of the results produced by the developed software with those obtained in the LabVIEW environment showed a good match, confirming the adequacy of the intelligent system. In addressing this problem, the primary objective was to ensure human comfort within the indoor environment rather than to conserve energy resources. Nevertheless, through the application of fuzzy climate control, energy savings of at least 9% were achieved.

Declaration on Generative AI

The authors have not employed any Generative AI tools.

References

[1] M. Han, B. Han, S. Liu, Z. Sun, Impact of microclimate on people's experiences and behaviours in the cultural consumption space: a case study of panjiayuan antique market in Beijing, China. Buildings, 13(5) (2023) 1158. doi: 10.3390/buildings13051158.

[2] Q. Yi, D. Nho, L. Kenneth, N. Duc, N. Thien, M, Tuan. Investigating the relationship between microclimate factors and human exercise performance from the perspective of citizen science. Human Factors in Sports, Performance and Wellness, 150 (2024) 38–48. doi: https://doi.org/10.54941/ahfe1005288.

[3] K. Y. T. Lim, M. A. N. Duc, M. T. N. Thien, R. Yuvaraj, J. S. Fogarty, Investigating the effects of microclimate on physiological stress and brain function with data science and wearables. Sustainability, 14 (2022) 10769. doi: 10.3390/su141710769.

[4] T. Sharmin, K. Steemers, Effects of microclimate and human parameters on outdoor thermal sensation in the high-density tropical context of Dhaka. International journal Biometeorol, 64 (2020) 187–203. doi: 10.1007/s00484-018-1607-2.

[5] C. Yang, M. Liu, M. Zhan, C. Lyu, Z. Fan, Research on the influence of microclimate on recreation behavior in urban waterfront public space, in: Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia, CAADRIA'21, Hong Kong, 2021, pp. 417–426.

[6] A. A. Ragheb, R. Aly, G. Ragheb, H. Mohamed, R. A. Ashmawy, Influence of building height on microclimate and human comfort: a case study from the new administrative capital. International Journal of Sustainable Development and Planning, 19(7) (2024) 2559–2568.

[7] M. Jokanović-Dajić, A. Koprivica, The impact of the microclimate parameters on the labor productivity, in: Proceeding of the 21th National and 7th International Conference in Quality System Condition for Successful Business and Competitiveness, CQSCBC'19, Kopaonik, KraljeviCardaci, 2019, pp. 21–29.
[8] M. B. Richardson, P. Li, J. M. Gohlke, D. B. Allison, Effects of indoor thermal environment on human food intake, productivity, and comfort: pilot, randomized, crossover trial. Obesity (Silver Spring), 26(12) (2018) 1826–1833. doi: 10.1002/oby.22328.
[9] Z. Deng, B. Dong, X. Guo, J. Zhang, Impact of indoor air quality and multi-domain factors on human productivity and physiological responses: a comprehensive review. Indoor Air, 2024 (2024) 25. doi: 10.1155/2024/5584960.
[10] T. Shao, Indoor environment intelligent control system of green building based on PMV index. Advances in Civil Engineering, 2021 (2021) 11. doi: 10.1155/2021/6619401.
[11] S. H. Kim, H. J. Moon, The performance of reinforcement learning for indoor climate control devices according to the level of outdoor air particulate matters. Buildings, 13(12) (2023) 3062. doi: 10.3390/buildings13123062.
[12] A. Banjac, H. Novak, M. Vasak, Implementation of model predictive indoor climate control for hierarchical building energy management. Control Engineering Practice, 136 (2023) 105536.
[13] H. Wang, I. Kolmanovsky, M. R. Amini, J. Sun, Model predictive climate control of connected and automated vehicles for improved energy efficiency, in: Proceedings of the Annual American Control Conference, ACC'18, Wisconsin Center, Milwaukee, USA, 2018, pp. 828–833. doi: 10.23919/ACC.2018.8431051.
[14] M. M. Mazar, A. Rezaeizadeh, Adaptive model predictive climate control of multi-unit buildings using weather forecast data. Journal of Building Engineering, 32 (2020) 101449.
[15] I. Olenych, Smart home climate control system based on fuzzy logic controller. Electronics and Information Technologies, 17 (2022) 26–35. doi:10.30970/eli.17.3.
[16] A. Berouine et al. A Fuzzy Logic-Based Approach for HVAC Systems Control, in: Proceedings of the 6th International Conference on Control, Decision and Information Technologies, CoDIT'19, Paris, France, 2019, pp. 1510–1515. doi: 10.1109/CoDIT.2019.8820356.
[17] J. Riahi, H. Nasri, A. Mami, S. Vergura, Effectiveness of the fuzzy logic control to manage the microclimate inside a smart insulated greenhouse smart cities, 7 (2024) 1304–1329. doi: 10.3390/smartcities7030055.
[18] L. Zh. Sansyzbay, B. B. Orazbayev, Modeling the operation of climate control system in premises based on fuzzy controller. Journal of Physics: Conference Series, 1399(4) 4 (2019) 1–7. doi:10.1088/1742-6596/1399/4/044017.