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## Integration of the NNARX Model in Python/Keras for Predictive Microclimate Control of Industrial Premises

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**Abstract.** The paper presents an approach to integrating an NNARX neural network model into the Python/Keras software environment for implementing predictive control of the microclimate in industrial premises as part of a cyber-physical system. The choice of the NNARX architecture as the predictive core of the control system is justified, and the specifics of its software implementation using the TensorFlow/Keras library are described. The structure of the software is presented, including a module for data acquisition and preprocessing of sensor data, a prediction module based on the trained NNARX model, and a control action generation module using a fuzzy logic controller. The results of experimental studies are provided, confirming the effectiveness of the proposed solution: the root mean square error of temperature prediction is 0.302 °C, the mean absolute error is 0.248 °C, and the temperature deviation from the setpoint under real operating conditions does not exceed 0.5 °C. It is shown that integrating the predictive model into a closed-loop control system reduces the stabilization time by 10–15% compared to classical PI controllers.

**Keywords:** NNARX, Python, Keras, predictive control, microclimate, cyber-physical system, neural network, TensorFlow, intelligent control.

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Ensuring the stability of microclimate parameters in industrial premises is a relevant scientific and technical task that requires the development of intelligent control systems capable of adapting to changing operating conditions. Traditional automatic control systems based on PI and PID controllers provide acceptable stabilization accuracy under steady external conditions; however, their efficiency significantly decreases in the presence of system nonlinearity, transport delay, and simultaneous influence of multiple disturbances.

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The response of the industrial environment to changes in control actions is not instantaneous and is determined by the thermal inertia of the premises, spatial distribution of zones, and the nature of technological loads. The presence of these factors justifies the transition to predictive control strategies based on forecasting the future state of the microclimate using neural network models.

The transition from reactive to predictive control requires a mathematical model capable of reproducing the dynamics of the control object with sufficient accuracy. Among the known neural network architectures for time series forecasting, the NNARX (Neural Network AutoRegressive with exogenous inputs) model deserves particular attention, as it combines an autoregressive structure with the ability to process external exogenous variables. Formally, the NNARX model is described by the following relationship:

$$y(t + 1) = F(y(t), y(t - 1), \dots, y(t - ny), u(t), u(t - 1), \dots, u(t - nu)) \quad (1)$$

where  $y$  – predicted microclimate parameter,  $u$  – vector of exogenous input variables,  $ny$  and  $nu$  – delay orders of the output and input variables, respectively,  $F$  – a nonlinear function implemented by a neural network.

The use of the autoregressive component provides the model with internal memory, allowing it to account for the inertial properties of thermal and ventilation processes and to reproduce the accumulative nature of changes in microclimate parameters.

The choice of the NNARX architecture for the predictive control of microclimate is обусловлено several factors. First, the autoregressive component enables the model to consider previous values of the predicted variable, which is critically important for systems with significant thermal inertia. Second, the presence of exogenous inputs makes it possible to incorporate the influence of external factors and control actions into the model, allowing it to generate forecasts depending on planned changes in actuator operation. Third, the NNARX architecture is computationally efficient compared to recurrent networks such as LSTM and GRU, as it does not contain internal feedback loops and is implemented as a feedforward network with an extended input vector, which is particularly important for real-time operation on industrial controllers.

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The software implementation of the NNARX model is carried out using the Python programming language and the TensorFlow/Keras library, providing sufficient flexibility for configuring the neural network architecture, training it on experimental data, and integrating it with the hardware of a cyber-physical system. The model is implemented as a Sequential architecture, including a Flatten layer for transforming input data, two hidden Dense layers with ReLU activation functions consisting of 32 and 16 neurons respectively, and an output layer with a single neuron and linear activation for generating the predicted temperature value. The choice of the ReLU activation function for hidden layers is обусловлено its ability to mitigate the vanishing gradient problem, which is particularly relevant when training deep neural networks, as well as its computational simplicity, which accelerates both training and inference.

Data preparation for training the NNARX model includes several stages. The initial dataset contains values of external temperature, indoor humidity, CO<sub>2</sub> concentration, fan speed, and heating system state, collected at 10-second intervals. At the first stage, all parameters are normalized to the range from zero to one using the MinMaxScaler transformation, ensuring equal contribution of each variable to the training process and preventing dominance of parameters with larger value ranges. Then, a set of training samples is formed using a sliding window approach, where each sample consists of three consecutive time steps of input data, and the target variable is the temperature value at the next time step. This approach allows the model to capture short-term dynamics and generate forecasts based on previous observations.

The model is trained using the Adam optimizer, which combines the advantages of stochastic gradient descent with adaptive learning rates, and the mean squared error loss function. The training process runs for 50 epochs with a batch size of 16 samples, while 20% of the data is reserved for validation. To prevent overfitting, early stopping, L2 regularization of weights, and dropout techniques are applied, where random neurons are periodically deactivated during training, forcing the network to learn more robust and generalized dependencies. The trained model is saved in .h5 format and loaded into the prediction module for generating control actions in real time.

Integration of the NNARX model within the cyber-physical

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microclimate control system involves close interaction of three software modules. The data acquisition module performs cyclic reading of temperature, humidity, and gas concentration sensor data via the RS-485 interface using the Modbus RTU protocol, applies filtering and normalization, and stores the results in a local SQLite database. The prediction module loads the trained NNARX model, forms an input vector based on recent observations, and generates a temperature forecast for the next time step. The control module receives both the predicted value and current measurements, generates decisions using a fuzzy logic controller, and transmits commands to actuators via the Modbus protocol. The modules interact with a periodicity of 10 seconds, ensuring timely system response to changes in microclimate parameters.

The hardware platform of the system is based on the KSP-08.L controller running a Linux operating system, supporting Python script execution and integration with sensor infrastructure via built-in RS-485 and Ethernet interfaces. The controller is equipped with a touchscreen for local monitoring and configuration and supports communication with higher-level automation systems via Modbus TCP. The MR100-24.02.2 data acquisition module provides analog and digital input/output for sensors and actuators. The sensor subsystem includes temperature sensors with a measurement range from  $-30$  to  $+60$  °C and accuracy of  $0.5$  °C, relative humidity sensors with an error not exceeding 3%, and CO<sub>2</sub> sensors with a range up to 5000 ppm and accuracy of 50 ppm.

The results of experimental studies confirm the effectiveness of the developed software solution. Training the NNARX model on real-world data yielded a mean squared error of 0.091, a root mean square error of  $0.302$  °C, and a mean absolute error of  $0.248$  °C. During field tests under industrial conditions, the control system maintained air temperature within a deviation not exceeding  $0.5$  °C from the setpoint, despite external temperature fluctuations of  $5-7$  °C and humidity variations of 10-15%. Transient processes exhibited a monotonic behavior without overshoot, and the stabilization time ranged from 3 to 5 minutes. The summarized results of the comparative analysis are presented in Table 1.

The use of a predictive-adaptive algorithm based on the NNARX model provides a 10-15% reduction in stabilization time compared to classical PI controllers, while periodic retraining of the model using accumulated operational data reduces the mean absolute prediction error by 12-15%. The

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absence of overshoot ensures smooth operation of actuators and reduces peak loads on heating, ventilation, and air conditioning systems, which positively affects their service life and energy efficiency.

Table 1

**Microclimate Control Systems: Key Performance Comparison**

Indicator	PI Controller	NNARX + fuzzy controller
Control principle	Reactive based on current deviation	Predictive based on state forecast
Prediction error, °C	Not applicable	MAE = 0.248; RMSE = 0.302
Setpoint maintenance accuracy, °C	1.0-1.5	0.5
Stabilization time, min	4-6	3-5
Presence of overshoot	Observed	None
Adaptation to changing conditions	Manual override	Automatic through model retraining

An important advantage of the developed software solution is its scalability and portability. The use of the standard Keras library allows the model to be trained on a workstation with subsequent export in .h5 format and deployment on an industrial controller without the need for recompilation or code modification. The software structure is built on a modular principle, enabling replacement of individual components, such as the neural network architecture or the fuzzy control algorithm, without affecting other system modules. In addition, integration with an SQLite database ensures the accumulation of historical data, which is used for periodic retraining of the model and improving prediction accuracy as operational experience grows.

**Conclusions.** The paper presents an approach to integrating an NNARX neural network model into the Python/Keras software environment for implementing predictive control of the microclimate in industrial premises. The architecture of the neural network, the data preparation methodology, the training algorithm using overfitting prevention techniques, and the structure of the software system consisting of data acquisition, prediction, and control action modules are described.

The results of experimental studies confirmed that the developed system provides high prediction accuracy and temperature stabilization with a deviation not exceeding 0.5 °C from the setpoint, a 10-15% reduction in stabilization

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time compared to traditional controllers, and no overshoot.

Further research should focus on the implementation of Edge AI methods for deploying predictive models directly at the microcontroller level, the development of digital twins of industrial premises for virtual optimization of control modes, and the expansion of system functionality by enabling simultaneous prediction of multiple microclimate parameters, including humidity and gas concentration.

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