Application of fuzzy logic methods for controlling buildings
HVAC equipment

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Abstract. This article represents an application of fuzzy logic methods for control purposes of heating, ventilating and air conditioning (HVAC) of modern buildings. Analysis of the main parameters of space comfort leads to the justification of fuzzy logic methods and definition of research goals. This research suggested a composition of linguistic variables and knowledge database for a virtual room air conditioning model which was simulated in MATLAB (Simulink) environment. The analysis of the modelling results proved that fuzzy methods demonstrate acceptable control capabilities and can be successfully implemented in practice. The work has been carried out within the course of studying the prospects of development of building management and automation (BMS) in the future.

1. Introduction
BMS currently integrates about 40% of all energy consumers (ventilation, heating, air conditioning, etc.) [1]. Energy efficiency forms the main optimization task alongside with providing comfortable conditions inside the building. This complex task, which arose together with the appearance of the first housings, has recently been reformulated from the standpoint of modern achievements in the fields of control, data processing and artificial intelligence. In 1981, the American company United Technology Building Systems (UTBS) Corporation used the concept of “Intelligent building” (IB), which gradually formed a new approach to building management. This approach integrates all the components of the infrastructure into a single system with the active usage of modern computing tools, methods of data processing and transferring. One of the achievements of technical progress in this field was the application of the theory of fuzzy logic, suggested by L. Zadeh in 1965 [2]. Later in 1974, Mamdani [3] showed the prospects of using the fuzzy logic ideas to build a dynamic object control system, and a year later, Mamdani and Assilian published a work describing a fuzzy PI controller and its use for controlling a steam generator. Since then, the field of application of fuzzy controllers is constantly expanding, increasing the variety of their structures and functions. On practice it was recently implemented for the construction and building industry [4, 5, 6].

2. Classic approach
Classic approach to control building HVAC equipment is to use a well-proven proportional-integral-differentiating controller (PID controller), invented in 1910 [7]. The classical automatic control system
with a feedback is shown in Fig.1, where block $R$ is a controller, $P$ is the control object, $r$ is the control action or setpoint, $e$ is the signal mismatch or error, $u$ is the controller output, and $y$ is the control variable.

![Figure 1. PID controller in a system with feedback](image)

The control output for this controller is calculated by formula:

$$u(t) = K \cdot e(t) + \int_{0}^{t} e(t) dt + T_a \frac{de(t)}{dt}$$  \hspace{1cm} (1)

The PID controller is the most common type of controllers. About 90...95% of regulators currently used on practice are based on the PID algorithm [7, 8]. The simplicity, clarity of operation, ease of setup and tuning have determined its high popularity for solving most practical problems. Among the few problems of using these regulators, are the difficulties of tuning on objects with a high degree of nonlinearity, which are subject to excessive noise and external disturbances, as well as problems of automatic adjustment and adaptation [9].

Fuzzy logic methods represent an alternative approach to control complex nonlinear objects and allow to overcome some disadvantages of the PID controller.

3. Fuzzy logic
A person's feelings about the comfort of the room have a subjective nature. They cannot be defined unambiguously and certainly. However, the existing methods of maintaining temperature, humidity, and other building parameters are aimed at controlling numerical fixed values. Fuzzy logic methods became the bridge that joins two ways of describing reality - fuzzy human and definite machine. Numerical variables are combined with words and form a new type of variable, which the creator of the fuzzy set method, L. Zadeh, in his first works, called a linguistic variable [2].

Currently, the Mamdani algorithm is the most widely used algorithm applied for fuzzy modelling problems. It is followed by algorithms suggested by Sugeno, Larsen, and some other authors which have their application in certain areas too [10, 11, 12, 13].

4. Study goals and methods
The purpose of this research work is to perform an analysis of fuzzy logic algorithms and their application for building equipment, their ability to overcome the disadvantages of PID controllers, complementing and working in combination with them. The first step in this search is to model the building's air conditioning system.

Fig.2 demonstrates a typical air conditioning unit that provides heating or cooling of the supply air for some occupied space.
The main purpose of this unit is to maintain the room temperature at a desired level. The following is the list of elements with their relationship, and control strategies.

Element 1 - indoor room temperature sensor.
Element 2 - outdoor temperature sensor.
Element 3 - hot water heat exchanger which performance can vary from 0 to 100%.
Element 4 - cold water heat exchanger.

For the diagram above, the simplified equation of heat balance, taking into account heat losses through external barriers, has the form:

\[ Q_{\text{air}} = Q_{\text{heater}} + Q_{\text{lost}} \]  \hspace{1cm} (2)

where \( Q_{\text{air}} \) is the thermal energy of the room's air; \( Q_{\text{heater}} \) is the flow of heat entering the room with the supply air from the heater (or cooler); \( Q_{\text{lost}} \) is the flow of heat leaving the room during the cold period (or entering the room during the warm period) through external walls.

\[ Q_{\text{air}} = \frac{M \cdot \lambda \cdot \Delta T}{3.6} \]  \hspace{1cm} (3)

where \( M \) is the mass of air that passed through the heater; \( \lambda \) is the specific heat capacity of the air (1 KJ/(kg·°C)); \( \Delta T \) is the change in temperature inside the room.

The amount of energy spent on heating (cooling) is equal to:

\[ Q_{\text{heater}} = \int_{t=0}^{t_n} P(t) \, dt \]  \hspace{1cm} (4)

where \( P \) is the power of the heater (cooler).

The amount of energy entering (leaving) the room through the boundaries:

\[ Q_{\text{lost}} = \frac{S \cdot \Delta T_{\text{ambient}}}{R} \]  \hspace{1cm} (5)

where \( \Delta T_{\text{ambient}} \) is the temperature difference between outside and inside the room; \( S \) is the surface area of the boundaries (walls, windows, floor, ceiling); \( R \) is the resistance to heat transfer.

The transition function corresponding to the specified heat balance model is an aperiodic element of the first order \([11, 12]\) described by formula:

\[ T \cdot \frac{dy}{dt} + y = k \cdot x \]  \hspace{1cm} (6)

Or in Laplace space:

\[ W(p) = \frac{k}{T \cdot p + 1} \]  \hspace{1cm} (7)

MATLAB application with Simulink visual modelling package can be used to build a simulation model using fuzzy logic methods \([13]\). The simulation methods allow to easily determine the main features and limitations of the fuzzy logic controller for managing building equipment. Fig.3 shows an simplified diagram of the simulation model.
The input linguistic variables are defined as follows:

- Temperature error or difference between the current room temperature and desired value, $e$
- The integral error, $\sum e$
- Differential error, $\Delta e$ (time derivative of error $e$)

It might be noted that the choice of input parameters for a fuzzy controller coincides with the discrete implementation of the PID controller output signal calculation, where the control signal formula has the form:

$$u(n) = K_p \cdot E(n) + K_i \cdot \sum_{k=0}^{n} E(k) + \frac{K_d}{T} \cdot (E(n) - E(n-1))$$  \hspace{1cm} (8)

The only output linguistic variable is:

- Signal for cooling or heating, $\tilde{u}$

This signal will be used to dictate the position of the valves on the hot and cold heat exchangers.

The structure of the fuzzy controller is shown in Fig.4. Three input variables after fuzzification are processed through the block of fuzzy controller to obtain the fuzzy control output $\tilde{u}$, which after the operation of defuzzification becomes a crisp controller output $u$ applied to the object.

**Figure 3.** Simulink simulation model diagram

**Figure 4.** Block diagram of a fuzzy controller

The diagram of the fuzzy controller, showing the fuzzy variables, is shown in Fig.5.
For the input variables $e$, $\sum e$, $\Delta e$, we select the Gauss distribution functions shown in Fig.6 – 8.

**Figure 5.** Fuzzy variables within fuzzy controller

**Figure 6.** Membership functions for error $e$

Here, when choosing the names of term sets, the names $e = \{"NL", "NM", "NS", "Z", "PS", "PM", "PL"\}$ are used, according to the commonly accepted notation system [9]: N-negative (Negative); Z-zero (Zero); P-positive (Positive); the letters S (small, small), M (medium, medium), L (large, Large) are added to these designations.

**Figure 7.** Membership functions for input $\sum e$
Triangle functions were selected for the output variable $\tilde{u}$ as shown in Fig.9.

### 5. Knowledge base

When compiling the knowledge base, the dimension of the input vector and the number of possible combinations should be taken into account. Theoretically, the number all possible combinations of input variables for this example should be 125. Table 1 contains few samples of knowledgebase.

| Rule | Condition $e$ | Condition $\sum e$ | Condition $\Delta e$ | Result $\tilde{u}$ |
|------|---------------|---------------------|-----------------------|---------------------|
| 1    | $Z$ (Steady)  | $Z$ (Steady)        | $Z$ (Steady)          | $Z$ (Steady)       |
| 2    | $Z$ (Steady)  | PS (Slightly hot)   | PS (Slightly positive)| NS (Slightly cooling) |
| 3    | $Z$ (Steady)  | NS (Slightly cold)  | NS (Slightly negative)| PS (Slightly heating) |
| 4    | PS (Slightly hot) | PS (Slightly hot) | Z (Steady)         | NS (Slightly cooling) |
| 5    | PS (Slightly hot) | PS (Slightly hot) | PS (Slightly positive)| NM (Medium cooling) |
For defuzzification of the resulting control action $\tilde{u}$, the fuzzy Mamdani inference mechanism is used. This approach is convenient for its clear visualization, which represents the centre of the area located under the resulting membership function [7]. An alternative method could be the method proposed in the works of Takagi-Sugeno-Kang. This method has some advantages for programming controllers that are not adapted for fuzzy logic.

Results of the simulation are shown in Fig.10 - 16. At the initial indoor temperature of 10 °C, after minor fluctuations within 2 °C, the system enters a stationary mode and maintains the temperature setpoint of 20 °C (Fig.10). In this case, the error signal $e$ (Fig.11) and the derivative of the error $\Delta e$ (Fig.12) are stabilized near zero synchronously with the temperature graph. The oscillation amplitude of the accumulated integral error $\Sigma e$ decreases slowly over time (Fig.13), which raises the question of the inexpediency of using this parameter for future experiments.

It should be noted that controller allows the smooth operation of the actuating valves (Fig.15, 16), which are fully opened only at the initial moment of time and then demonstrate a certain time delay when the control action $u$ changes (Fig. 14).
Figure 13. Graph of changes in $\Delta e$

Figure 14. Control action graph $u$

Figure 15. Schedule for changing the position of the cooling valve

Figure 16. Graph of changing the position of the heating valve
6. Conclusions
Analysing the results of the first stage of research, it can be noted that the fuzzy logic algorithms allow to create control systems that demonstrate reasonable performance and accuracy for heating or cooling processes simulated in a virtual model of the air-conditioning system. The research area is promising to their application to the HVAC systems.

The next stages of research should include:
- A composition of a complex ventilation system and include additional control parameters such as carbon dioxide or humidity in the room;
- Conduct comparative tests of a classical control system based on a PID controller and a system based on fuzzy logic;
- Evaluate the stability of the system based on fuzzy logic, as well as evaluate the quality of the regulatory process;
- Consider alternative options of hybrid control systems that combine several methods.

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