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Design and Validation of a Mamdani-Type Fuzzy Inference System for Dynamic Indoor Climate Balancing

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ABSTRACT

The goal of this research is the design, simulation, and validation of a stable and energy-efficient Mamdani-type-1 FLC that controls an indoor climate balancing system by overcoming the drawbacks of conventional linear control in handling the intrinsic nonlinearity and complexity of the system. The main objective will be to dynamically control crucial climate parameters such as Fan Speed and Cooling Rate based on crisp input values of Temperature in the range [8 44] and Relative Humidity in the range [0 90]. The operational intelligence of the FLC relies on a comprehensive fuzzy rule base of thirty-five (35) IF-THEN rules that connect seven fuzzy sets for temperature and five for humidity to their corresponding output actions. The simulation also highlights the capability of the FLC to smoothly offer nonlinear control transitions from minimum to maximum effort, thus avoiding abrupt on/off behavior that wastes energy. This research validates the FLC as an effective, feasible, and energy-efficient control solution, laying a very firm foundation for further research.

Keywords— Fuzzy Logic Controller, Indoor Climate Balancing, Mamdani Inference, HVAC System, Fuzzy Rule Base

INTRODUCTION

Indoor Climate Balancing Systems, consisting of HVAC (heating, ventilating, and air conditioning) systems and RAC (refrigeration and air conditioning) systems, are a significant area for management since they account for a large portion of building energy consumption globally [1-3]. Energy consumption is critical for any interior climate balancing system; therefore, the goal should be to reduce energy consumption while maintaining appropriate and acceptable indoor temperatures for the occupants [1-2].

Conventional control practices adopted for HVAC systems, such as ON/OFF or Proportional-Integral-Derivative (PID) controllers, often struggle to capture the complex nature of HVAC equipment, including nonlinear system dynamics, parameter uncertainties, and time-varying characteristics [1-2]. Optimal climate control demands the concurrent control of Temperature and Relative Humidity [4-5]. Linear control strategies underperform because they are insufficient for controlling the nonlinear features of air-conditioning systems, which behave as multiple-input multiple-output (MIMO) systems with closely linked parameters [2].

Among the intelligent control techniques, Fuzzy Logic Controllers arise as one of the most advanced and efficient alternatives to surpass the limitations of conventional control systems [6]. Fuzzy logic systems imitate the way humans think by implementing linguistic principles, which make it possible to handle nonlinear and mathematically complicated systems without the need for a detailed mathematical representation [4, 6-7]. Therefore, the goal of this study is to take advantage of the merits of FLC in developing a multi-output fuzzy model that would dynamically balance inputs like temperature and humidity with control outputs like fan speed and cooling rate, thus reducing energy consumption and enhancing the efficiency of the system.

In most parts of the world, HVAC systems are one of the largest electrical power consumers, utilizing about 40% to 60% of a building's total energy consumption [1]. The operation of HVAC systems continues to be more challenging due to the complexity and nonlinearity of the system and because it is a multi-input, multi-output device with interconnected characteristics that cannot be optimally regulated by standard linear control methods such as PID [2, 8]. From a performance point of view, conventional controllers often control temperature and humidity, the two most important comfort variables, leading to poor performance, energy losses, and wear of actuators through oscillation or unexpected changes [2, 9]. Therefore, FLCs are applied in intelligent control systems, which can handle complexity and uncertainty without explicit mathematical modeling of the system [10-11].

The intelligent control system will act to adjust the important climate parameters, such as Fan Speed and Cooling Rate, based on the assessment of inputs like Temperature and Relative Humidity, which would help to overcome inadequacies related to handling the system's inherent nonlinearity and complexity by conventional linear controllers.

The following specific objectives will be useful in achieving this overall goal:

1. To establish the architecture of the FLC including the selection of Mamdani-type inference for efficient operation in HVAC/RAC applications.

2. To characterize the input variables, Temperature and Humidity, with appropriate ranges and linguistic labels, and define the resulting output control actions, Fan Speed and Cooling Rate, along with their respective ranges and linguistic labels.

3. To map crisp input values, such as Temperature and Humidity, to fuzzy linguistic sets ("Cold," "High") through appropriate membership functions in the fuzzification stage of the control system.

4. To construct a comprehensive set of IF-THEN rules that replicate human reasoning and govern the necessary control actions for maintaining an optimal indoor climate based on the coupled Temperature and Humidity inputs.

5. To implement and simulate the designed FLC model using MATLAB and test its performance across various indoor conditions, ensuring the FLC provides stable, adaptive, and energy efficient control actions.

METHODOLOGY

The research methodology on designing and implementing the Indoor Climate Balancing System using a Mamdani-type Fuzzy Logic Controller includes system modeling, design steps specific to the FLC, and performance validation as illustrated in Fig. 1.

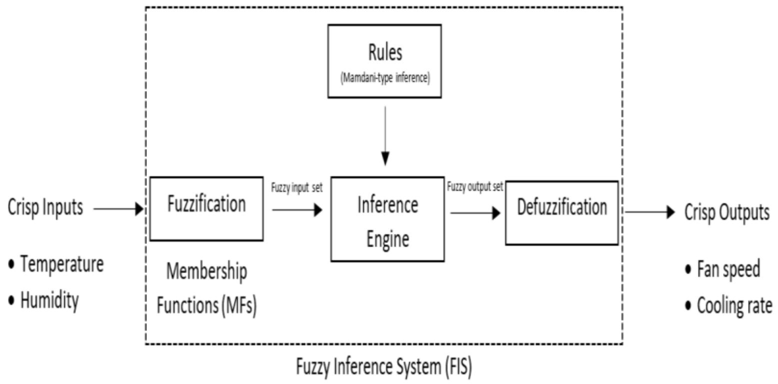

Fig. 1 System Design Diagram

A fuzzified controller is a type of tool that takes real world measurements, converts them into fuzzy values, refines them by rule-based inference machine, and finally transforms fuzzy output values into definite control signals [7]. The FLC serves as the backbone of the system and utilizes the Mamdani-type inference, one of the most widely applied in HVAC/RAC applications [7]. The sequence in fuzzy logic starts with inputting numerical values (Crisp Inputs) from the sensor, e.g., indoor temperature and humidity. In contrast to crisp inputs, the

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Fuzzy Inference System uses fuzzy-like terms or can be described as subjective linguistic terms. For example, a temperature reading of 30°C is converted into a degree of membership for the linguistic sets "Warm" or "Hot" using membership functions (MFs).

This fuzzified data is sent into the Inference Engine, which uses a set of IF-THEN rules (for example, IF Temperature is "Warm" AND Humidity is "High," THEN Cooling Rate is "Medium"). To select the fuzzy output, the Inference Engine follows the procedure of human reasoning, usually using Mamdani-Type (Max-Min) inference 7. The last process is the Defuzzification, which reconverts the fuzzy output into a practical, crisp value. Outputs, which are a precise signal, are then assigned to Fan Speed and Cooling Rate to maintain the desired environmental conditions.

Table I Table of Variables

Parameter	**Type**	**Range**	**Linguistic Labels**
Temperature	Input	[8 44]	Cold, Cool, Normal, Warm, Hot, Very Hot, Extremely Hot
Humidity	Input	[0 90]	Very Low, Low, Normal, High, Very High
Cooling Rate	Output	[0 3]	Extremely Low, Very Low, Low, Normal, High Very High, Extremely High
Fan Speed	Output	[0 100]	OFF, Low, Medium, High, Max

Table 1 shows that the FLC for the Indoor Climate Balancing System is designed to use two different input control variables: Temperature and Humidity. A temperature input ranges between 8 and 44 and is described by seven linguistic labels: Cold, Cool, Normal, Warm, Hot, Very Hot, and Extremely Hot. The second input, Humidity, ranges between 0 and 90 and is described by five linguistic labels: Very Low, Low, Normal, High, and Very High. It is important to mention that these numeric ranges of Temperature and Humidity were taken from the methodology in reference [6, 12] to make the system applicable within the context of indoor climate control.

These fuzzified inputs, processed by the Fuzzy Inference Engine using the rule base, determine the system's two outputs: Fan Speed and Cooling Rate. The Fan Speed has a numeric range of 0 to 100 and uses five linguistic labels: OFF, Low, Medium, High, and Max. On the other hand, the Cooling Rate is highly limited in its range of 0 to 3, and is controlled by seven linguistic labels: Extremely Low, Very Low, Low, Normal, High, Very High, and Extremely High. In general, this structure enables the FLC to convert the fuzzy perception of the indoor climate-through the defined input sets-into precise, granular crisp commands in both the intensity of cooling and the velocity of airflow, maintaining the desired indoor climate condition.

The operational intelligence of the FLC is embedded within its comprehensive Fuzzy Rule Base, comprising thirty-five (35) distinct IF-THEN rules shown in Figure 2. These rules are developed to try and emulate human decision-making and expert knowledge by using the logical AND operator that links the two input linguistic variables: Temperature (e.g., Cold, Normal, Hot) and Humidity (e.g., Very Low, Normal, High), while each of the rules then prescribes the control action for the two output linguistic variables: Fan Speed (e.g., OFF, Low, Max) and Cooling Rate (e.g., Extremely Low, Normal, Extremely High). For example, a rule might be: "IF Temperature is Hot AND Humidity is High THEN Fan Speed is Max, Cooling Rate is Very High." Such a complicated network of rules provides an option for the FLC to estimate precisely which mix of fan speed and cooling intensity is proper under all possible combinations of temperature and humidity conditions for adaptive, stable, and energy-efficient climate control. The systematic enumeration of these rules covers the entire input space, guaranteeing an efficient and responsive system performance.

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	Rule	Weight	Name
1	If Temperature is Cold and Humidity is Very Low then Fan Speed is Off, Cooling Rate is Extremely Low	1	rule1
2	If Temperature is Cold and Humidity is Very Low then Fan Speed is Off, Cooling Rate is Extremely Low	1	rule2
3	If Temperature is Cold and Humidity is Normal then Fan Speed is Low, Cooling Rate is Extremely Low	1	rule3
4	If Temperature is Cold and Humidity is High then Fan Speed is Low, Cooling Rate is Very Low	1	rule4
5	If Temperature is Cold and Humidity is Very High then Fan Speed is Medium, Cooling Rate is Low	1	rule5
6	If Temperature is Cool and Humidity is Very Low then Fan Speed is Off, Cooling Rate is Very Low	1	rule6
7	If Temperature is Cool and Humidity is Low then Fan Speed is Low, Cooling Rate is Very Low	1	rule7
8	If Temperature is Cool and Humidity is Normal then Fan Speed is Low, Cooling Rate is Very Low	1	rule8
9	If Temperature is Cool and Humidity is High then Fan Speed is Medium, Cooling Rate is Low	1	rule9
10	If Temperature is Cool and Humidity is Very High then Fan Speed is Medium, Cooling Rate is Low	1	rule10
11	If Temperature is Normal and Humidity is Very Low then Fan Speed is Low, Cooling Rate is Very Low	1	rule11
12	If Temperature is Normal and Humidity is Low then Fan Speed is Medium, Cooling Rate is Low	1	rule12
13	If Temperature is Normal and Humidity is Normal then Fan Speed is Medium, Cooling Rate is Low	1	rule13
14	If Temperature is Normal and Humidity is High then Fan Speed is High, Cooling Rate is Low	1	rule14
15	If Temperature is Normal and Humidity is Very High then Fan Speed is High, Cooling Rate is Normal	1	rule15
16	If Temperature is Warm and Humidity is Very Low then Fan Speed is Medium, Cooling Rate is Normal	1	rule16
17	If Temperature is Warm and Humidity is Low then Fan Speed is Medium, Cooling Rate is Normal	1	rule17
18	If Temperature is Warm and Humidity is Normal then Fan Speed is High, Cooling Rate is Normal	1	rule18
19	If Temperature is Warm and Humidity is High then Fan Speed is High, Cooling Rate is Normal	1	rule19
20	If Temperature is Warm and Humidity is Very High then Fan Speed is Max, Cooling Rate is High	1	rule20
21	If Temperature is Hot and Humidity is Very Low then Fan Speed is High, Cooling Rate is Normal	1	rule21
22	If Temperature is Hot and Humidity is Low then Fan Speed is High, Cooling Rate is High	1	rule22
23	If Temperature is Hot and Humidity is Normal then Fan Speed is High, Cooling Rate is High	1	rule23
24	If Temperature is Hot and Humidity is High then Fan Speed is Max, Cooling Rate is Very High	1	rule24
25	If Temperature is Hot and Humidity is Very High then Fan Speed is Max, Cooling Rate is Extremely High	1	rule25
26	If Temperature is Very Hot and Humidity is Very Low then Fan Speed is High, Cooling Rate is High	1	rule26
27	If Temperature is Very Hot and Humidity is Low then Fan Speed is Max, Cooling Rate is Very High	1	rule27
28	If Temperature is Very Hot and Humidity is Normal then Fan Speed is Max, Cooling Rate is Very High	1	rule28
29	If Temperature is Very Hot and Humidity is High then Fan Speed is Max, Cooling Rate is Extremely High	1	rule29
30	If Temperature is Very Hot and Humidity is Very High then Fan Speed is Max, Cooling Rate is Extremely High	1	rule30
31	If Temperature is Extremely Hot and Humidity is Very Low then Fan Speed is Max, Cooling Rate is Very High	1	rule31
32	If Temperature is Extremely Hot and Humidity is Low then Fan Speed is Max, Cooling Rate is Extremely High	1	rule32
33	If Temperature is Extremely Hot and Humidity is Normal then Fan Speed is Max, Cooling Rate is Extremely High	1	rule33
34	If Temperature is Extremely Hot and Humidity is High then Fan Speed is Max, Cooling Rate is Extremely High	1	rule34
35	If Temperature is Extremely Hot and Humidity is Very High then Fan Speed is Max, Cooling Rate is Extremely High	1	rule35

Fig. 2 IF-THEN Rules

RESULTS AND DISCUSSION

The implementation of the research for indoor climate control, details the design and application of a Mamdani Type-1 Fuzzy Logic Control system. The goal of the implemented intelligent system is to analyze the automation of cooling systems by applying fuzzy logic rules based on temperature and relative humidity parameters to control the surrounding air and power consumption for indoor environment. The system automatically controls the cooling devices when the temperature varies between 0 °C to 50 °C and relative humidity varies between 0% to 90% which was adapted in the previous researches on Fuzzy logic systems [6, 12].

The core intelligence is managed by the FLC, which was designed and simulated using the MATLAB platform. The model utilized the Mamdani's method Type-1. The Mamdani FIS was chosen because it includes an output membership function, unlike the Sugeno FIS. The schematic of the fuzzy system is composed of three major components (Fuzzification, Fuzzy Inference System, and Defuzzification). For the fuzzification, the crisp inputs (Temperature and Humidity) are mapped to fuzzy sets. Seven (7) triangular fuzzy sets are selected for the input temperature [12], and five (5) triangular linguistic fuzzy sets are selected for relative humidity [6]. While the Fuzzy Inference System will produce the output according to the system inputs, utilizing thirty-five (35) IF-THEN rules that are constructed with the AND operation. These rules convert the degrees of membership for the inputs into an output fuzzy set. Lastly, the Defuzzification generates specific fuzzy output values resulting from the inference system and converts them into crisp values to manage the cooling system mode setting.

Table II Simulation Results

Test No.	Input 1	Input 2	Expected Output	Actual Output [FS CR]	System Response / Observation
1	15	30	FS will be at low range and CR will be Low	[50 1.5]	The system responds in a stable, but forceful manner. The Fan Speed (medium range) with a non-zero Cooling Rate (Normal range) is adaptively neutral. The model views the state as mildly cool but not excessively dry and on the threshold of its comfort zone.
2	17	61	FS will be at low range and CR will be	[95.7 2.89]	The system response is stable and subtle. This is low sensitivity because even though the conditions are not exactly

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			Extremely Low		Normal, the system resists forceful action, instead of accelerating the fan and creating a significant amount of cooling. This adaptive stability maintains the system operating with very little energy and not over-correcting for the minor humidity issue near the optimal temperature of the room.
3	26	45	FS will be at medium range and CR will be normal	[60.4 1.87]	The system reacts rapidly and adaptively with medium-to-high outputs. This reaction demonstrates the system is sensitive to discomfort, automatically engaging a medium range fan speed and using a significant amount of cooling. It is stable because the outputs are a balanced trade-off across several active rules, indicating it can adjust to situations between its primary comfort levels without merely maxing out.
4	38	28	FS will be at max range and CR will be very high	[79.1 2.37]	The system responds fully and strongly with high efficiency. This is evidence of high sensitivity to extreme heat, instantly demanding a lot of cooling and high speed of the fan. But the Cooling Rate is slightly dragged below the maximum since the humidity is low, indicating the system is adaptive and able to slightly modify its effort according to dryness, while being fully stable in its effort to lower the temperature.
5	40	79	FS will be Max and CR will be Extremely High	[95.7 2.89]	The system reacts rapidly and forcefully with the greatest possible outputs. The reaction is most sensitive to the inputs, calling for an extremely high effort to cool and dry out at once, which demonstrates its immensely adaptive to extreme conditions and fully stable in providing the most reasonable action.

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The simulation effectively demonstrates the Mamdani Type-1 FLC system's ability to provide a stable and adaptable indoor environment control. There are thirty-five (35) IF-THEN rules with seven (7) fuzzy sets for temperature and five (5) for humidity which are the primary process utilized in computing the FS and CR outputs. The outputs show that the system is highly adaptive and can perform subtle decisions rather than a conventional on/off switch. For example, under near ideal conditions (i.e., 15 °C and 30 % humidity), the non-zero Cooling Rate and low fan speed exemplify adaptive neutrality rather than the forcing of action that wastes energy. At the highest rating for temperature and humidity, for instance, 40°C and 79% relative humidity respectively, the system is most sensitive with both outputs controlled as near to their maximum, FS and CR at 95.7 and 2.89 respectively, as practical in attempt to make quick comfort correction feasible. This smooth transition from zero effort to a maximum output seeks to show the FLC model as a workable and practical method for the automation of climate balancing systems.

The results of the simulation can be visually represented by the Figure 3 and Figure 4 Surface Viewer, which graphically illustrates the relationship between the two input variables-the Temperature and Humidity-and the two dynamically controlled output variables-Fan Speed and Cooling Rate. These surfaces confirm the effectiveness of the Mamdani Type 1 FLC in providing smooth, stable, and adaptive control across the full range of possible environmental conditions.

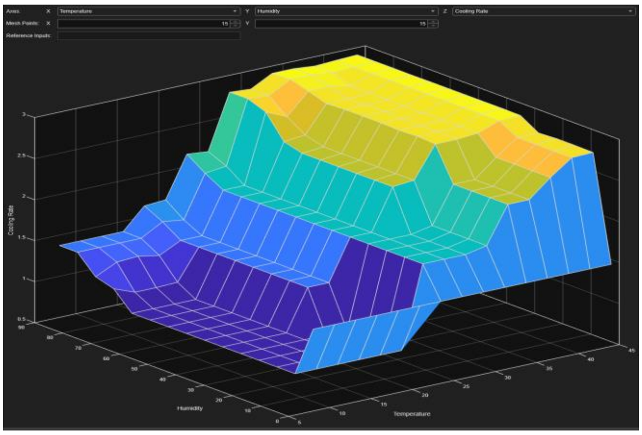

Fig. 3 Cooling Rate Surface

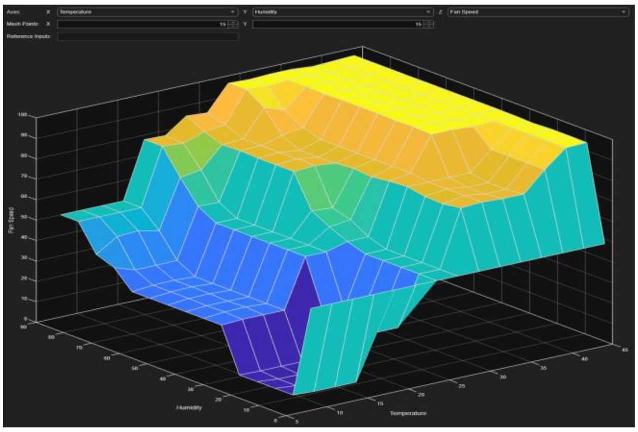

Fig. 4 Fan Speed Surface

Fig. 3 presents a clear, logical control strategy for CR surface, whose output (Z-axis) increases smoothly as the inputs (X and Y axes) move away from the ideal comfort zone. Similarly, Figure 4 shows a highly correlated output, which is expected since the fan is supposed to distribute the cooled and dried air. Close to the ideal comfort zone, the FS output assumes a low or zero setting, confirming the low sensitivity and subtlety in the system response. For increasing temperature and humidity inputs, the Fan Speed smoothly ramps up to its maximum range, ensuring the immediate, fast dissemination of cooling required for correcting extreme conditions to retain stability and realize the most reasonable action. The continuous, nonlinear shape of both the control surfaces confirms that the FLC provides a smooth transition from zero effort to maximum output, avoiding the suboptimal performance and actuator wear caused by the oscillations typical of conventional on/off controllers.

Similarly, from Figure 4, the output is highly correlated, as would be expected from a fan that is supposed to disseminate the cooled and dried air. For a temperature and humidity input close to the ideal comfort zone, the FS output assumes a low or zero setting, confirming that the response of the system is of low sensitivity and subtlety. With increasing temperature and humidity inputs, the Fan Speed smoothly ramps up to its maximum range in order to ensure the immediate, fast dissemination of cooling required for the correction of extreme conditions to retain stability and realize the most reasonable action. The continuous, nonlinear shape of both control surfaces confirms that the provided FLC offers a smooth transition from zero effort up to a maximum output, avoiding suboptimal performance and wear of actuators due to the oscillations typical of conventional on/off controllers.

The continuity of both 3D surfaces and their non-linear behavior prove that FLC manages a smooth transition from zero effort to maximum output. The FLC also avoids the abrupt, energy-wasting on/off behavior typical for conventional controllers. Based on the graphical validation, the Mamdani FLC would be a feasible, practical, and robust solution to automate climate-balancing systems while optimizing energy efficiency.

CONCLUSIONS

Design and simulation proved that the Mamdani Type 1 FLC successfully achieved the objective of stable and energy-efficient control in Indoor Climate Balancing Systems. Replacing the complex, nonlinear mathematical modeling of MIMO systems, such as HVAC, it embodies a computationally simple, robust control structure based on human-like linguistic reasoning. With a total of thirty-five IF-THEN rules based on seven fuzzy sets for Temperature and five for Humidity, the prominent adaptivity of the FLC was demonstrated with smooth transitions of the outputs-Fan Speed and Cooling Rate-from subtle, non-zero actions near the ideal comfort conditions to a maximum required effort in extreme environmental states. This finally justifies the FLC model presented here as feasible and practical for automation of climate-balancing systems, which is continuously optimized for energy efficiency compared to conventional methods.

Although the FLC model was robust in simulation, one of the major limitations is that these findings are based solely on the Mamdani inference method. No comparative study was conducted against other prominent fuzzy models; thus, absolute performances and computational efficiency relative to alternatives remain unidentified. It is highly recommended to conduct a comparative study of the present FLC against other fuzzy inference models, specifically the Sugeno model and ANFIS models, in future research. Such a comparative study will be imperative for full validation of the findings and to identify, beyond any doubt, the most effective and computationally superior model for implementation in a real-world indoor climate balancing system.

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