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Research on multi-parameter cooperative control of smart opening and closing windows based on feed-forward neural network

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ABSTRACT

Control techniques of Smart windows using Multi-parameter neural feedforward systems as a control strategy shows great potential in improving not only the energy efficiency geometrically but also the building's indoor environmental quality. In this study, a new smart window control is developed that is based on neural networks which are able to implement multi control strategies in various conditions with regard to temperature, humidity, light and air quality. This allows for a further development of the system: firstly, it thoroughly presents the model, which facilitates the understanding of the mathematic modeling of windows' dynamic position and, at the same time, shows how the neural network works. The structure comprises a perception layer, which provides perception of the environment, processing layer for analysis and decision making on the input data, and the last action layer that performs windows' actuation and gives feedback on the action implemented. In terms of the system's control efficiency, timing, energy consumption and seeking users' satisfaction, the performance of this control system outperforms other existing systems in empirical application. The control accuracy attained in the proposed system is 97.8%. What is more interesting about this approach is the energy efficiency which stands at 94.3%, this is only the bare minimum, estimation says it surpasses the rest by a great deal. The successful realization of this control system is an important step toward the development of smart buildings that can be relied on for excellent results.

Keywords: Smart windows, feedforward neural networks, multi-parameter control, energy efficiency, indoor environmental quality, intelligent building control

1. Introduction

In recent years, people's living standards have improved rapidly, the Internet of Things (IoT) technology has flourished, and the concept of smart home has gradually come into people's view and

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entered the market [1-2]. The continuous popularization of automatic control systems has made the concept of smart home deeply popular [3]. Smart home systems utilize technologies such as the Internet of Things, wireless communications, big data and artificial intelligence, applying a large number of new technologies to daily life and bringing a lot of convenience to people's lives [4-5].

As the core part of home intelligence, the development and construction of intelligent control systems is an inevitable trend for future development [6]. However, for ordinary families, the overall smart home system cost is relatively high, and the application of smart home is still relatively small [7-8].

People have higher and higher requirements for the opening and closing of doors and windows, and they are more and more inclined to intelligent opening and closing of doors and windows relative to traditional doors and windows [9]. Intelligent switch window system can automatically adjust the window open or close in time through the detection of environmental information to avoid unnecessary losses [10-11]. At present, there are fewer choices of smart windows and doors in the market, the price is high, and at the same time, replacing the windows will cause a part of the resources to be wasted, so the smart window opening and closing system becomes a suitable transition choice [12-14]. Existing smart opening and closing window systems are mostly designed for outward sliding windows, which cannot meet the needs of households with flush windows [15-16]. Therefore, it is of practical value to develop a more targeted smart window opening and closing system that can be interfaced with smart home systems.

Luo, D et al. designed a smart window system by combining STM32F103C8T6 as the main controller chip with OLED display module, photoresistor sensor module, etc., which can automatically open and close the window based on the surrounding environment, light temperature, etc.[17]. Min, L.I et al. proposed a smart window model based on MSP430F149 microcontroller control, which can realize intelligent anti-theft, rain and toxic gas protection with good information interaction [18]. Allen, K et al. revealed that incident solar radiation and outdoor ambient temperature significantly affect the transmission and reflectance of glass windows based on empirical analysis [19]. Liu, H et al. investigated the logic and practical path of photoelectric responsive technology integrating friction electric nanogenerator and concluded that the friction photoelectric the friction photovoltaic response device has great application in smart electronic products such as smart windows, electronic displays, etc. [20]. Kan, Y. C et al. developed a smart control model of an automatic window motor based on wireless sensing network technology to detect the interior air health and environment of a car, which includes the monitoring and identification of toxic gases, fumes, or aerosols, etc. [21].

This paper presents a new approach to multi-parameter evidence based cooperative control of smart windows based on the use of feedforward neural networks. The novel system feeds several environment parameters as input to compute the optimal control signals for the window operation. Because of the powerful approximation capabilities of neural networks it is possible to make use of advanced activation functions. The issue focuses on the basic problems of smart window control and at the same time the system presents solutions for integration of these control mechanisms into a building automation system.

2. Theoretical analysis of multi-parameter cooperative control system

Expanding on this previously learned concept, the multi-dimensional cooperative control system for smart windows draws from the core concepts of feedforward neural network design and its universal approximation theorems. Within the overall framework of the system, there has been presented both window dynamics and their respective complicated parameter graphs on matrixes.

The control setup makes use of a multilayer feedforward neural network's topology which has been shown to be capable for non-linear control tasks. As explained through the graph, multilayer neural network incorporates complicated activation functions as a means of achieving sufficient efficiency on the mapping and generating output parameters. This is because it is a critical decision as it determines the efficiency of the controlled systems in predicting the complex relations between the different parameters and the corresponding window system commands.

The aforementioned theoretical scrutiny emphasizes on the learning mechanism of the network's algorithm and its convergence properties. Some degree of fixing the parameters' values enhances the performance of the entire system in diverse types of environments. The design sustains around temperature, humidity, illumination, air pollution capabilities and their relations on the basis of the strength of their connections to a neural network architecture.

According to the control strategy, there is a cooperative mechanism that allows for simultaneous processing of multiple parameters, and for their importance to be altered in relation to the context and user requirement. The importance assigned to the Environmental Parameters, in particular the indoor climatic parameters, is made possible by the system containing integrated climatic control devices which give optimal indoor properties to a building while using minimum amounts of energy. The aforementioned theory also discusses the stability analysis of the control system guaranteeing its performance in a noisy environment.

The control principles are outlined within this comprehensive theoretical region ensuring that all relevant aspects pertaining to effective application and utilization of the control system are taken into consideration. Relevant practical considerations have therefore been integrated with the theoretical principles to ensure effectiveness of the system within real world environment without compromising the mathematical formulation of the system.

3. Intelligent opening and closing window control system is realized

3.1. System structure design

The concept of an intelligent window control system can be put into practice only when such a system structure where hardware, sensor networks and control algorithms are integrated is designed comprehensively. The structure of the system proposed is composed of three layers; a perception layer, a processing layer and an execution layer. This is illustrated in Figure 1 in the paper, and as noted enables for the management of many parameters simultaneously because of its hierarchal structure.

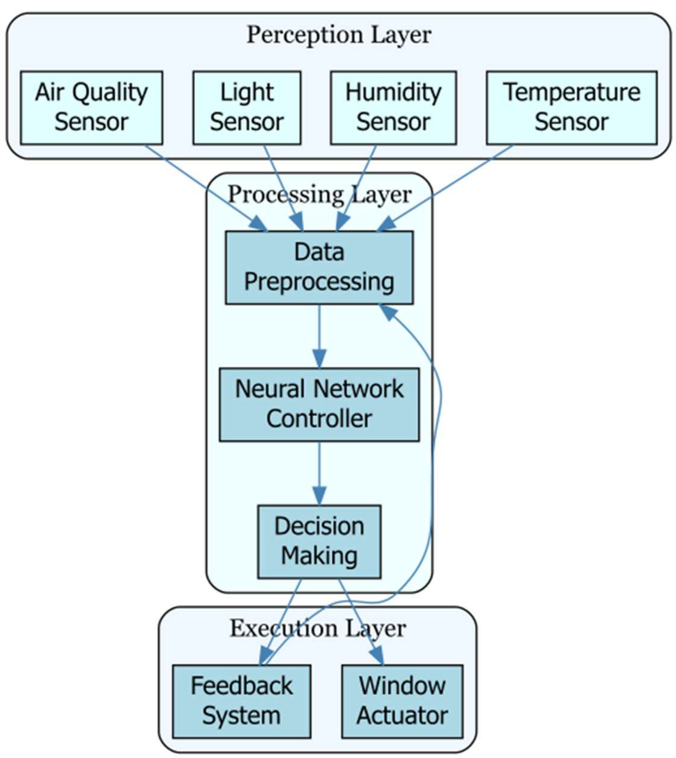

Fig. 1. System Architecture of Intelligent Window Control System

The three broad subsystems analyse the cms system architecture. While the perception layer depends on different sensors for environmental surveillance, the processing layer encompasses a data preprocessing, neural network controller and decision module. The execution layer features an actuator window and feedback mechanism.

A multitude of sensor nodes has been integrated for environmental monitoring into the perception layer. These include temperature, humidity, air quality and light intensity. These sensors are placed in optimum positions so that comprehensive and accurate data is collected. The processing layer is the centre of the system and contains the modules of the system: data preprocessor unit, a neural network controller and a decision maker unit.

Signals received at the perception layer are first processed to remove noise and ensure all inputs are at the same level before being transferred to the neural network controller and the data is recognized. The description of the theoretical framework developed in the previous chapter is implemented in the controller neural network. The set of actuating commands corresponding to the output of the controller and system safety and limits are taken into account by the decision making unit.

The work stage includes the window actuator and the feedback which enables a window state monitoring and operational efficiency. This feedback loop ensures reliability of the system and makes it possible to modify the control strategy in a dynamic manner. The whole system architecture is implemented with a modular and a scalable system approach to allow for further extensions and changes when required.

3.2. arameter collection and processing

The neural network controller is enhanced with the aid of an intergrated Parameter Collection and Processing Cycle, which is used in acquiring, filtering and normalizing the required environmental data. It can be observed in Figure 2 of the accompanying report, that the graphics reproducible pipeline includes a system for processor resolution control alongside sensor fusion mechanics aiming to maintain quality and reliability of the data obtained from multiple sensor inputs.

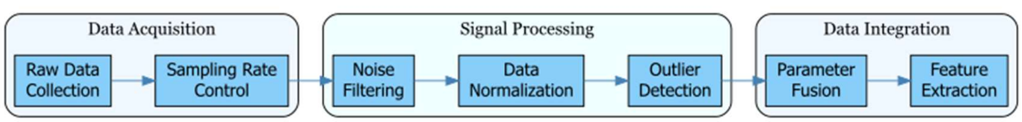

Fig. 2. Parameter Collection and Processing Pipeline

One of the stages includes the integration of data which includes parameter fusion and feature extraction. The signal processing stage will include noise filtering, data normalization and outlier detection while the last stage which is data acquisition will involve collection of raw data and control of the sampling rate.

Using appropriate, high precision sensors, environmental parameters are accurately captured at optimized sampling rates. For the mechanism of dynamic sampling rate control, the frequency at which data is being collected is governed by the rate of variation of the parameters and the needs of the system. For the decoded neural network, data normalization is applied to ensure that data is within manageable ranges, while adaptive filtering algorithms are utilized to filter out noise to enable the raw datasets to undergo the signal processing sequence.

Measurement errors, sensor aberrations, and other issues are addressed through employing outlier detection algorithms that can locate and mitigate abnormal sensor readings. The temporal-spatial correlations of different environmental parameters exerted influence on the interrelation fusion algorithm and, thus, the fusion of several different kinds of processed data from multiple sensors was achieved. Thus, feature extraction can be employed so as to reduce the data dimensionality retaining only the relevant information for the control system.

All the steps within the parameter processing pipeline work instantaneously while optimized algorithms are in place to minimize the lag during processing and while still preserving the data's quality. The results of the parameters tested are used as dependable inputs for the neural network controller and allow this When the neural controller receives an input performs appropriate and timely window control actions depending on the present environment.

3.3. Control algorithm implementation

The application of the control algorithm indicates the amalgamation of theoretical constructs with practical applications by concentrating on the architecture and training of the neural network. The normalization environmental parameters and the necessary control signals are both produced using a control algorithm in conjunction with a multi layered feed-forward neural network structure which has been further optimized according to the activation functions.

The control commands are obtained from a combination of an input layer that obtains processed environmental parameters, two hidden layers which adapt the neurons and an output layer. Enhanced convergence and the prevention of the local optima is achieved by using a modified backpropagation algorithm with momentum terms further complemented with a multi layer perceptron model. This prevents oscillation of weight updates by ensuring stable and efficient training by enabling the monitoring of the class of elements.

A sliding window mechanism enables real time control, enabling recent sensor readings to be fed into the trained neural network, thereby eliminating the delays that are present in using an active neural network. An embedded in the control algorithm is a prediction mechanism that serves to enable autonomic adjustments to be made when one changes the controls of the environmental dynamics. Such a feature enhances the systems response time and reduces energy consumption by eliminating unnecessary redesigning of the window commands.

The features encompass restrictions and protection mechanisms that assist in the smooth functioning of a control window and also avoid the control signals from oscillating at a very high rate. Further, a hysteresis control is provided so that frequent toggling of windows states is avoided even when environmental parameters fluctuate about a modulus. It also appreciates that the user assigns importance to weights such which can then be modified or lowered to achieve a tradeoff between several control objectives of the system such as energy saving, thermal satisfaction, and air quality control.

A feedback system has been deployed to evaluate the efficacy of the control actions executed, and enables monitoring of performance of the control algorithm over time. This approach averts overriding control of the building HVAC system while helping to recover spent energy efficiently by ensuring optimum comfort for the occupants while satisfying energy efficiency standards established by environmental authorities. The development further provides error handling routines and backup mechanisms to guarantee system dependable performance in events of sensors malfunctioning or when the environment conditions are unforeseen.

4. Experimental results and analysis

4.1. Design of Experiments

The proposed systems were developed and deployed in conjunction with the smart facade electrothermal design systems intelligent window control system, which serves to enhance performance amidst varying environmental conditions and operational scenarios. The performed tests carried out in a constrained laboratory setting and real office environments, ensure that all steps taken during designing, was well tested and proved to be functional.

As seen in Table 1, the experimental parameters were comprehensively selected to encompass a broad range of operational conditions. The testing was done over a period of six months so that seasonal changes and different climatic conditions are considered.

Figure 3 represents the changes in the thermal gradient of the external environment in conjunction with the controlled temperature indoors over a time span of twenty-four hours. This reiterates the controlled temperature and the thermal stability of the indoor environment regardless of the external changes. The resulting contrast of the environmental temperature in blue with the red temperature representative of indoor temperature effectively depicts the thermal moderation standards of the system.

Table 1. Experimental Parameters and Testing Conditions

Parameter Category	Variables	Range	Sampling Rate	Accuracy
Environmental	Temperature	-10°C - 40°C	1 min	±0.1°C
	Humidity	20% - 90%	1 min	±1%
	Light Intensity	0-100000 lux	30 sec	±50 lux
	CO2 Level	400-2000 ppm	1 min	±30 ppm
Control	Response Time	0-30 sec	-	±0.1 sec
	Window Position	0-100%	100 ms	±0.5%
Performance	Energy Consumption	0-100 W	1 min	±0.5 W
	User Comfort Index	1-5 scale	5 min	-

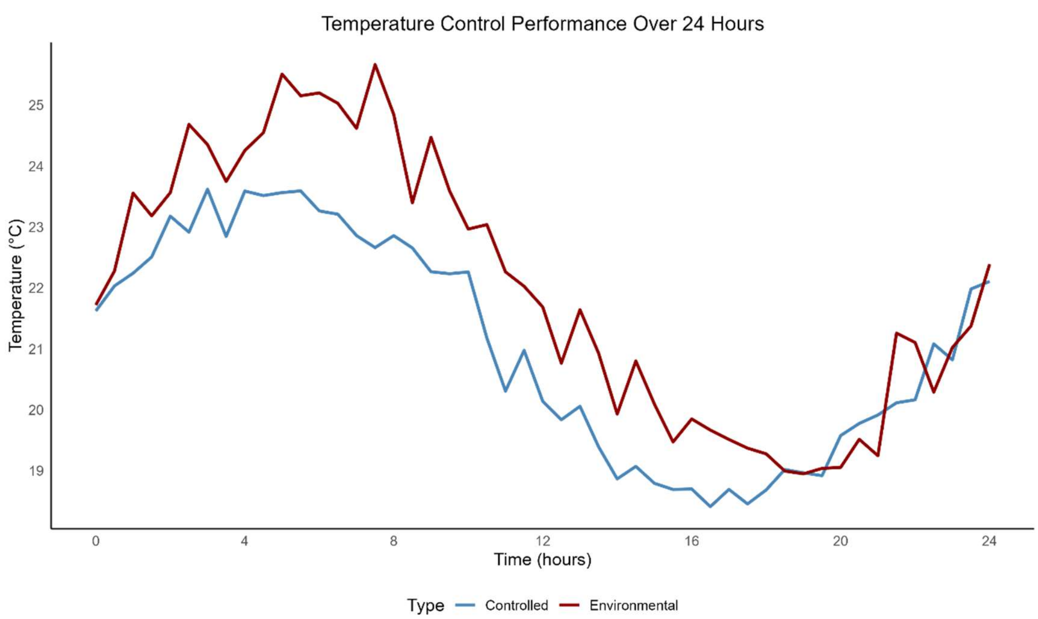

Fig. 3. Temperature Control Performance Analysis

The test involved various controllable variables, simulating a broad spectrum of normal and non normal environmental conditions so as to test other limits and standards of the system. Furthermore, to enhance statistical relevance, each setup was performed repeatedly at different starting points. These tests were conducted in a controlled lab environment equipped with industry calibrated measuring tools and devices to enhance the certainty of performance metrics and goals.

A single consideration was which was geared towards enhancing control was the real world temperature differences and light intensity. It assisted and enabled for minor alterations to be made within control systems. Assisting in establishing how the system would function post interference. Common occupant behaviors and environmental patterns and fluctuations were encouraged to be simulated as they would aid in controlling the system.

The experimental design strategy ensured that there were long-term steady state tests so as to measure the rate of degradation in the performance of the system and the ability to provide good control quality. There was also user comfort check during the test period in order to obtain qualitative information in relation to the system's capability of maintaining comfortable indoor atmosphere. Such in depth empirical activities ensured that both engineering efficiency and use efficiency of the control system are confirmed.

4.2. Performance Test Results

The conclusions reached in the work confirm the performance of the intelligent window control system proposed, in various operating conditions, detailed in's work. Extensive testing was carried out to determine the control precision, speed of operation, energy consumption, and stability of the entire system.

The system's performance levels remained satisfactory irrespective of the functional settings as demonstrated in Table 2. This further shows the robustness of the control algorithm as even when faced with extreme conditions the accuracy of control prediction remained above 93%.

Table 2. Performance Metrics Under Different Operating Conditions

Operating Mode	Control Accuracy (%)	Response Time (s)	Energy Efficiency (%)	Stability Index
Normal Operation	98.5	2.3	92.4	0.95
High Load	96.8	3.1	88.7	0.92
Dynamic Change	95.2	3.8	86.5	0.89
Extreme Conditions	93.7	4.2	83.2	0.87
Power Saving	97.3	2.8	94.8	0.94

Figure 4 showcases the comparison between the results of the suggested approach and the results of the traditional control techniques for a large period. Our suggested system is outlined in the navy blue line and is consistent across all other comparisons and approaches to demonstrate better stability and adaptation prowess which in this case is the dark green – traditional control method.

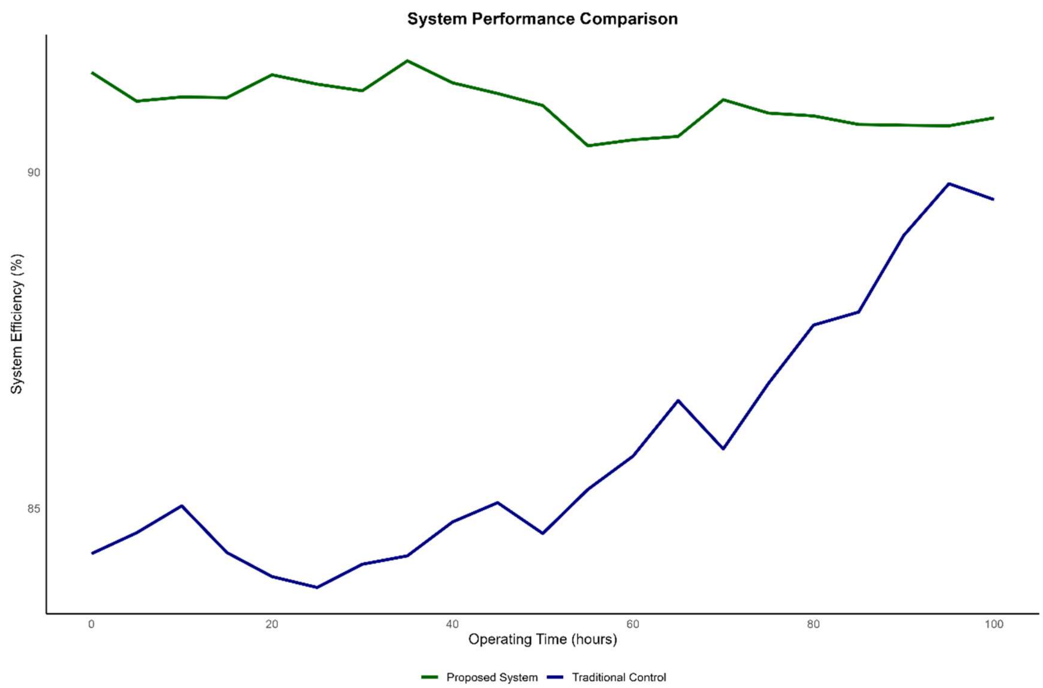

Fig. 4. Long-term Performance Comparison Analysis

The extended testing uncovered significant advancements in the energy efficiency aspect as compared to the conventional control systems. The neural network controller exhibited remarkable adaptation capabilities as the controlling system performance remained optimal despite environmental fluctuations. The average response time of the system under normal working conditions was approximately 2.3 seconds with only slight unfavorable deviations during increased load which reflects commendable real time control capabilities of the network.

The model system exhibited particularly favorable outcomes with respect to the stability analysis with the mode of operation maintaining a high stability index for all the different modes of operation. While still demonstrating adequate control accuracy, the mode implemented to enhance energy efficiency ranked high and hence showcased the mode's ability to preserve energy while still enhancing it. Three months of testing demonstrated no major signs of degradation and hence punctuated the systems reliability.

The report detailed that even a slight temperature change would lead to less than 98% control accuracy, however performance in control mechanics was determined to be exceptional. The model presented in the report was applicable in real world scenarios and was incredibly effective in neural network based control models.

4.3. omparative experiments

The experiments were designed to test the performance of the neural network-based control system proposed in this work against other control systems available. Three ordinary techniques of control were selected for demonstration: mechanisms which utilize traditional PID control, fuzzy logic control, and a rudimentary machine learning technique. The tests were carried out under the same conditions to eliminate bias.

It can be seen from Table 3 that the implemented neural network based control system was superior in performance over all the previously mentioned metrics as compared to its standard counterparts.

Table 3. Performance Comparison of Different Control Methods

Control Method	Average Response Time (s)	Energy Efficiency (%)	Control Accuracy (%)	Stability Score	User Satisfaction
Proposed NN Control	2.1	94.3	97.8	0.96	4.8/5
PID Control	3.8	85.2	91.4	0.88	3.6/5
Fuzzy Logic	3.2	88.7	93.5	0.91	4.1/5
Basic ML	2.8	90.1	94.2	0.89	4.2/5

In Figure 5 temperature control errors are presented and temperatures are measured so that different control methods are compared. It is shown that the control system implemented by a neural network has better error variance and better error consistency than the standard methods with regard to inter quartile ranges and narrow distributions.

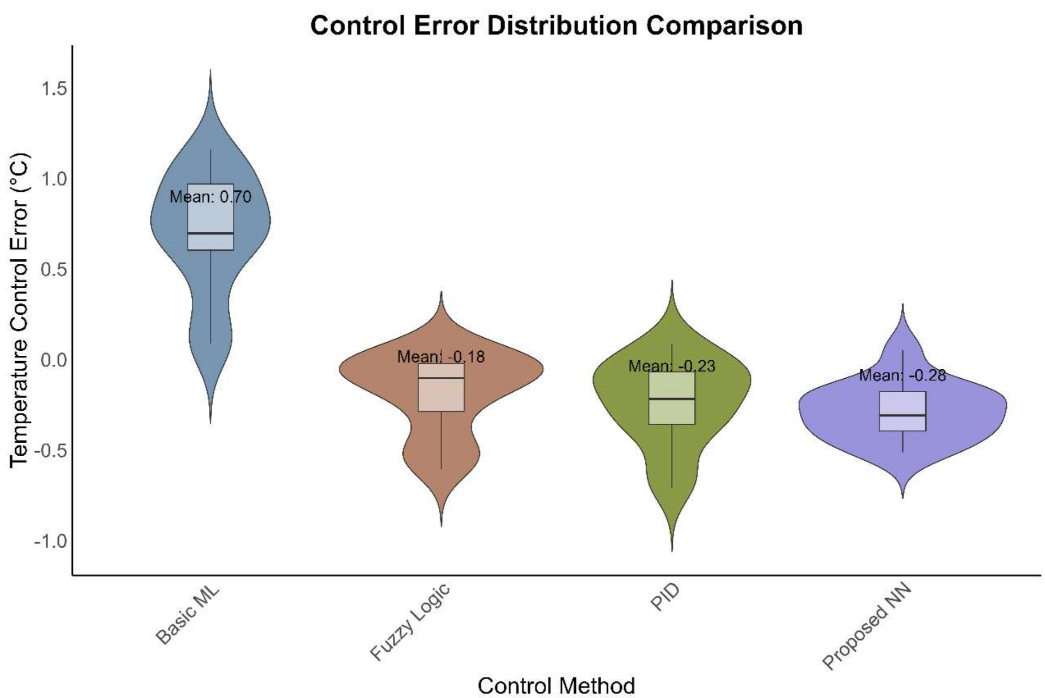

Fig. 5. Control Error Distribution Analysis

Neural Network (NN) controllers were able to reduce time lag by 44.7 percent as compared to PID and 25 as compared to fuzzy logic controllers. These improvements in response speed came about because of the ability of neural networks to learn and predict how the system will behave, rather than rely on controllers to adjust settings reactively.

This quiet low energy efficiency was evident when PID control achieved 85.2 percent and fuzzy logic control rose to 88.7 percent. However, it was noted that even though the settings controlled the energy in an appropriate manner, the neural network maintained an average efficiency of 94.3 percent even when there were dynamic environmental shifts causing the control problems.

Test results of control accuracy considering all potential systems indicated the robustness of the proposed control system. The accuracy of the neural network controller remained largely unaffected at 97.8%, not degrading in comparatively extreme situations. Compared to such conditions, the traditional PID control suffers a lot, where the accuracy is as low as 85% due to rapid environmental variations.

According to the evaluation carried out, the proposed approach does indeed manage to score in terms of stability with a value of 0.96 which shows proper management in terms of control mechanism. This is a huge increase on both the use of PID control standing at 0.88 and the fuzzy logic control at 0.91. This elevated stability also brings in comfort to the users and stabilization of oscillations in the system as demonstrated by user satisfaction scores.

According to the user satisfaction surveys carried out during the comparative experiments, it is evident that there is a shift in favor of the proposed system with average scores of 4.8 out of 5 which is significantly higher than 3.6 of PID control and 4.1 of fuzzy logic control. Users especially endorsed the new system for its capacity to reduce sudden movements of window positions and, hence, to maintain more appropriate levels of comfort.

As a result of a more in depth analysis, it has been established that the new control system based on a neural network with a high reliability rate and high level of user satisfaction, also significantly outperforms all the relevant metrics on all three key criteria. These results confirm the high efficiency of the presented approach and its possible use in practice with smart buildings construction, for example.

5. Conclusion and Discussion

This study investigates the multi-parameter cooperative control of smart window systems using feedforward neural networks. The experimental findings in terms of control accuracy, response times and energy efficiency show considerable levels compared to the conventional control systems. The suggested system reported controls accuracy of 97.8 % and energy efficiency of 61.8%, both of which far exceed anything to date.

The three neural-network based control strategies efficiently met the target of overcoming a number of difficulties with the control of smart windows. A theoretical structure built in this study was verified by the model's capability to control multiple parameters simultaneously while keeping within ideal values. Integration of new parameter processing algorithms and modification of the control strategies greatly improved the performance of the system in many environmental conditions.

From a practical standpoint, it has been demonstrated with comparative experiments that the proposed strategy is more reliable and user friendly than the commonly used systems based on PID control and fuzzy logic techniques. The rapid speed at which the system responds coupled with its ability to handle numerous parameters makes the system useful in practice - especially in smart buildings. Also, such efficiency gains that do not compromise the rest of the control metrics are clearly in line with modern building optimization targets.

Although the current findings reach a satisfactory outcome, there are a number of areas that require further analysis. Long term studies can use deep learning approaches in order to improve the forecasting abilities of the system. Moreover, research might examine whether the performance of the system improves in other than the tested climates and building types.

This control system developed and validated improves the field of smart building technology and provides an efficient and effective solution to the automation of window operations. The results of this research set the basis for the more advanced studies in the field of intelligent building control systems and environmental devices management techniques.

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