

Fuzzy Controller Algorithm for Automated HVAC Control

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Abstract –

This research presents the design framework of the artificial intelligent algorithm for an automated building management system. The AI system uses wireless sensor data or IoT (Internet of Things) and user's feedback together. The wireless sensors collect data such as temperature (indoor and outdoor), humidity, light, user occupancy of the facility, and Volatile Organic Compounds (VOC) which is known as the source of the Sick Building Syndrome (SBS) or New Building Syndrome because VOC are often found in new buildings or old buildings with new interior improvement and they can be controlled and reduced by appropriate ventilation efforts. The collected data using wireless sensors are post-processed to be used in the neural network, which is trained in accordance with the collected data pattern. When the users of the facility have the control of the building's ventilation system and the AI system is fully trained using the user input, it will mimic the user's pattern and control the building system automatically just as the user wants. In this research, data were collected from 4 different buildings: university library, university cafeteria, a local coffee shop, and a residential house. Fuzzy logic controller is also developed for better performance of the HVAC. Indoor air quality, temperature (indoor and outdoor), HVAC fan speed and heater power are used for fuzzified output. As a result, the framework and simulation model for the energy efficient AI controller has been developed using fuzzy logic controller and the neural network-based energy usage prediction model.

Keywords – IOT; AI; Neural Network; Fuzzy Controller; Smart Building

1 Introduction

The energy efficiency has become an urgent issue for sustainability of our society under global warming and it is closely related to infrastructure design such as buildings and the usage patterns of residents. Energy efficient buildings have evolved over decades, and

intelligent control systems have been adopted for efficient operations of the buildings. Next generation buildings will be smart buildings equipped with various sensors and autonomous control systems that interact with the users.

This research paper suggests an innovative and systematic approach in smart building management system for energy saving and sustainable development of society. Smart building means automated control of building systems such as lighting, heating and cooling, ventilation, security, etc. to provide the users productive and comfortable environment. Lighting, power meters, pumps, heating, and fire alarms are all connected and monitored as part of the building management system.

The authors of this paper have been working on developing wireless sensor network (WSN) to monitor indoor air quality and energy profiles, and this current paper aims at testing the WSN at real community facilities and developing a method for objectively evaluating the energy consumption patterns of the participating community organizations. This research suggests the preliminary investigation and study of feedback from the community participants regarding the deployment of the wireless sensor network and the integration of the feedback into the design of smart building management system. The smart buildings system will automatically control building functions such as lighting, heating, cooling, ventilation, security, etc. to provide occupants with more productivity and comfort.

2 Smart Building Technologies for Public Facility

2.1 Smart Facilities and the Community

In this project, the wireless sensors collected data from the buildings that are used in the community. Installed sensors are temperature, humidity, light, Volatile Organic Compounds (VOC) level, and movement sensors. The collected sensory data along with the user input will be fed to the Artificial Intelligent (AI) system, which learns the usage patterns and produces

similar outputs just like users control the air-conditioning and heating units. In addition to copying the usage pattern, the researchers will look for the way to improve energy efficiency by optimized control of building management system.

Artificial intelligent system using neural network and fuzzy logic algorithms is used to analyze the IoT data and controls the smart building systems. Volatile Organic Compounds (VOC) which is known as the source of the Sick Building Syndrome (SBC) is also monitored. The control of VOC can be done by controlling HVAC system. The authors have developed the pilot model of automated HVAC system as the proof-of-concept for the smart building system.

The authors of this research have been developing collaborative relations with several community partners for energy efficiency improvement in their public facilities. The testing facilities are (1) New Britain Police Station, (2) New Britain Public Library, (3) Hospital of Central Connecticut, and (4) YWCA at New Britain. The four different community partners have very unique characteristics in size, number of users, and the form of ownership as follows:

- (1) New Britain Police Station. The HVAC system is 20 years old and the system is very energy inefficient.
- (2) Public Library is management by the New Britain Foundation that is non-government, non-profit organization.
- (3) The Hospital of Central Connecticut (New Britain General) is very large facility with the daily float population is 80,000~100,000. Residents like doctors and nurses stay most of time in the building while visitors like patients and helpers are float population. User pattern analysis and customer feedback will be very beneficial to the development of adaptive smart building.
- (4) YWCA building in New Britain, CT has been renovated and expanded. The adaptive smart building system will be tested and compared on existing building and new expansion.

2.2 Energy Peak Demand Control

The authors of this papers have been with the local energy company in the state of Connecticut and New England area. The energy company can provide energy consumption of the buildings in real time monitoring the peak usage as well as low usage time. The peak power use is critical because more than maximum peak power usage may cause catastrophic power outage. The smart building helps alleviate the peak use and reduce the risk of the power loss. The researchers of this paper have designed artificial intelligent system for smart building management, and the community partners' energy usage data to be collected in this research will verify the effectiveness of the developed system.

3 Methods

Smart building systems are beneficial for both the owner and the users working within. These benefits range from energy savings to productivity gains to sustainability. They reduce energy consumption, increase the productivity of the users, improve building operations, support sustainability efforts and enhance decision-making across the organization for efficient use of optimal start/stop of HVAC system.

3.1 Artificial Intelligence in Building Management

Artificial Intelligent (AI), first introduced in the Dartmouth Conference in 1961, is a flexible rational system that perceives its input data and produces outputs that maximizes the goal. For example, if the energy cost saving while maintaining the user's comfort level is the goal, AI would provide the optimum heating/cooling operation scenarios.

3.2 Sensors and IoT

Smart sensors collect environmental information that can be processed to manage the facilities better for effective heating, cooling and electricity saving. Temperature, motion, vibration, light, and indoor air quality sensors such as VOC sensor are installed. They monitor occupancy and floating population to recognize the usage patterns, which are analyzed by artificial neural networks.

3.3 Interpretation of Sensor Data using Neural Network

The sensor data are collected, preprocessed and fed to the neural network to determine the usage patterns of the facility, which are recognized to produce the optimized operations of the smart buildings. Elevators, HVAC, lightings, security systems, and electrical usage of the buildings can be analyzed and optimized for the most energy efficient operation.

3.4 Fuzzy Logic Systems and Fuzzy Controller

User's inputs are verbal values or although it is in numerical scale, they are not exact number but they can be considered as fuzzy numbers or fuzzy membership functions which can have error tolerance. Fuzzy membership and membership functions is a simple and easy to use tool to convert verbal expressions in numerical values. For example, if user answers "very satisfied", "satisfied", "moderate", and "not satisfied" in the customer experience in new automated heating and cooling system, user's response can be converted into certain numerical representation in order to be used in

computer system.

4 The Development of Neuro-Fuzzy Controller for Smart Building

4.1 IOT Data Collection and Post Processing

The indoor sensors utilized in this research are (1) Temperature, (2) Humidity, and (3) Volatile Organic Compounds (VOC) that is considered as the main cause of the bad indoor air quality. Any materials that have chemical compounds such as new paints and new carpets can result in high VOC readings. VOC is also known as a cause of the Sick Building Syndrome (SBS). VOC can be monitored by IoT sensors and can be controlled automatically in the smart building systems.

In this research, data were collected in the Elihu Burritt Library and Devil's Den (Student Cafeteria) at Central Connecticut State University (CCSU). In addition to the indoor temperature and VOC, outside temperature and the number of people using the facility were monitored. The number of people in the facility was indirectly estimated by the wireless motion sensors. Persons sit still and not moving will not be detected. However, simple motion sensors provide an effective indirect way of measuring how the facility is used. The result of collected data are shown in the figures below.

The wireless sensors were tested and successfully utilized. The collected data are analyzed using neural network which is the machine learning algorithm for artificial intelligence systems. In order to complete the machine learning training and develop the robust smart HVAC system, the automated HVAC controller needs to be developed.

The researchers have tested the wireless sensors on the community facilities and the result is processed and fed to the feedforward neural network. The authors of the paper used simulated HVAC control data to develop the energy usage pattern analysis. The controlling system of HVAC is designed using fuzzy controller system.

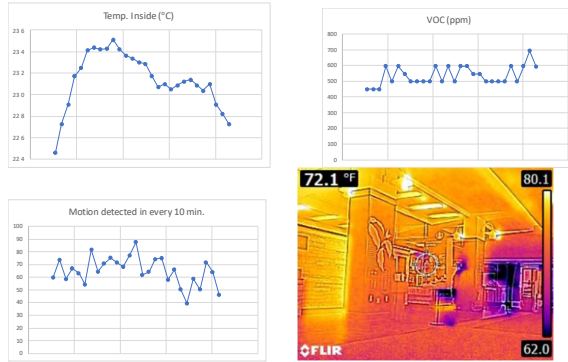


Figure 1. Wireless sensor data and infrared images at the library

The neural network model for the energy usage pattern utilizes the variables such as: Outdoor-Temperature, Number-of-occupancy, Time, Date, and Day. The variables such as Time, Date, and Day have been converted into 2-digit codes for the neural network pattern training purpose. The neural network for energy usage pattern recognition and energy usage prediction model has been developed and it is continuously being compared with the real energy consumption data. The more data are collected the better prediction model can be developed.

4.2 Fuzzy Controller

There are some research findings that compares traditional Proportional-Integral-Differential (PID) controller and fuzzy logic controller for heating and cooling system (Gouda et al. 2000, Attia et al. 2015). PID controller is considered reasonable and efficient alternative to the manual or simple on/off controllers of HVAC systems. However, recent studies showed that fuzzy logic controllers perform better than PID controllers when the users satisfaction level is considered. PID controller uses simple mathematical formulas of integration and differentiation of temperature changes over time, while fuzzy logic controller converts users' linguistic expressions into mathematical functions, and calculates the fuzzy if-then rules using fuzzy inferences.

Conventional PID controller can be shown as following equation,

$$u(t) = K_P e(t) + K_P K_I \int_{t=0}^t e(t) dt + K_P K_D \frac{de(t)}{dt} + u(0) \quad \text{eq. 1}$$

where K_P is the controller gain representing a proportionally constant between error and controller output, K_I is the reset constant relating the rate to the error in units of $[\%/(\% \cdot \text{sec})]$, K_D is the rate constant in units of $[(\% \cdot \text{sec})/\%]$, and $u(0)$ is the controller output at $t = 0$ (Tsoukalas 1997).

Once the fuzzy variables are defined, the fuzzy logic controller is simply shown as,

$$u(k) - u(k-1) = \Delta u^*(k) \quad \text{eq.2}$$

where $u(k)$ and $u(k-1)$ are temperature readings at time k and $k-1$ and Δu is the extent of change of the control variable u at time $t = k$ that is change in action and the defuzzified output is $\Delta u^*(k)$.

In this research, authors developed the fuzzy membership functions and inference rules to control the heater and indoor air quality. Defined fuzzy membership functions are: (1) Current Temperature and Humidity (indoor and outdoor) and forecast temperature and humidity; (2) Time, Day, Date, and holiday information; (3) Number of people; and (4) VOC (Volatile Organic

Compounds). The simulation model shown in this research, only the temperatures and VOC are fuzzified. The fuzzy controller was developed only the heating and indoor air quality control. The fuzzy membership functions are defined such as VH for very high and L for low, etc.

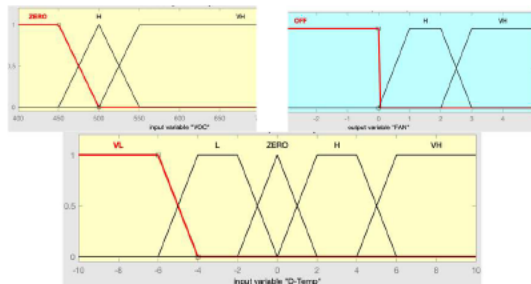
The outputs of the fuzzy controller are: HVAC fan speed and heater power. So, the fuzzy membership functions for HVAC fan speed are *VH*, *H*, and *OFF*, and fuzzy membership functions for heating power are *VH*, *H*, and *OFF*. The fuzzy controller inputs variables are crisp values such as: Temperature reading, temperature setting, and temperature differences (*D_Temp*) between temperature setting and temperature reading. Indoor air quality read by VOC sensor is also used as input variable. Figure 2 shows input, output variables and if-then rules.

The fuzzy controller for heating/cooling system has been created. Variables are the differences between the target VOC and current VOC level. If fuzzy variable *D_VOC* (differences of VOC level) can be defined as *Very_High*, *High*, and *Zero*. According to the fuzzy values of *D_VOC*, the HVAC control can be *High*, *Low*, and *Off*. In the same way, fuzzy variable *D_Temp* can be driven from the Temperature and Target-Temperature. The fuzzy controller delivers accurate control of the heating/cooling system for optimum temperature and VOC levels.

Fifteen sample fuzzy if-then rules were developed. Rules are very simple. If the temperature difference is high, turn the heater high, if the indoor air quality is low turn the fan high, and so on. Fuzzy if-then rules are defined as followings:

- R_1 : If *D_Temp* is *VL* and *VOC* is *H* then *HEAT* is *VH*(*FAN* is *VH*) *ELSE*
- R_2 : If *D_Temp* *L* and *VOC* is *VH* then *HEAT* is *H* and *FAN* is *VH* *ELSE*
-

By using the Mamdani-min for fuzzy implication, defuzzification results are shown as Figure 2. As an example, when *D-Temp* is 5°F and *VOC* is 600ppm, the controller settings will be 2.65 for heater and 3.65 for fan speed.



1. If (*D-Temp* is *VL*) and (*VOC* is *ZERO*) then (*HEAT* is *VH*)(*FAN* is *VH*) (1)
2. If (*D-Temp* is *L*) and (*VOC* is *ZERO*) then (*HEAT* is *H*)(*FAN* is *H*) (1)
3. If (*D-Temp* is *ZERO*) and (*VOC* is *ZERO*) then (*HEAT* is *OFF*)(*FAN* is *OFF*) (1)
4. If (*D-Temp* is *H*) and (*VOC* is *ZERO*) then (*HEAT* is *OFF*)(*FAN* is *OFF*) (1)
5. If (*D-Temp* is *VH*) and (*VOC* is *ZERO*) then (*HEAT* is *OFF*)(*FAN* is *OFF*) (1)
6. If (*D-Temp* is *VL*) and (*VOC* is *H*) then (*HEAT* is *VH*)(*FAN* is *VH*) (1)
7. If (*D-Temp* is *L*) and (*VOC* is *H*) then (*HEAT* is *H*)(*FAN* is *H*) (1)
8. If (*D-Temp* is *ZERO*) and (*VOC* is *H*) then (*HEAT* is *OFF*)(*FAN* is *H*) (1)
9. If (*D-Temp* is *H*) and (*VOC* is *H*) then (*HEAT* is *OFF*)(*FAN* is *H*) (1)
10. If (*D-Temp* is *VH*) and (*VOC* is *H*) then (*HEAT* is *OFF*)(*FAN* is *H*) (1)
11. If (*D-Temp* is *VL*) and (*VOC* is *VH*) then (*HEAT* is *VH*)(*FAN* is *VH*) (1)
12. If (*D-Temp* is *L*) and (*VOC* is *VH*) then (*HEAT* is *H*)(*FAN* is *VH*) (1)
13. If (*D-Temp* is *ZERO*) and (*VOC* is *VH*) then (*HEAT* is *OFF*)(*FAN* is *VH*) (1)
14. If (*D-Temp* is *H*) and (*VOC* is *VH*) then (*HEAT* is *OFF*)(*FAN* is *VH*) (1)
15. If (*D-Temp* is *VH*) and (*VOC* is *VH*) then (*HEAT* is *OFF*)(*FAN* is *VH*) (1)

Figure 2. Input/Output Variables and Fuzzy If-then Rules

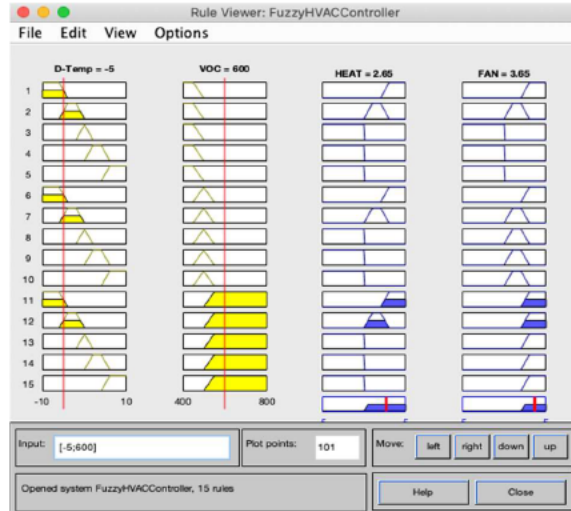


Figure 3. Fuzzy implication and defuzzification result for HVAC controller

5 Conclusions

The main advantage of the developed neural network prediction system and fuzzy logic controller is that it will deliver precise control of the heating/cooling system as well as energy consumption prediction models for different temperature and VOC target levels. The predictive system operates the HVAC pre-emptively saving energy cost and more efficient use of the heating/cooling system. Fuzzy logic controller makes precise control of HVAC improving comfort of the users.

In this research, fuzzy logic controller algorithm is developed only for the heater and indoor air quality control. Neural network prediction model was developed for HVAC usage prediction but the energy saving results and analysis are still under development.

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