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A pilot study of occupant centric control stratum ventilation based on computer vision

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Abstract. Indoor occupant information has an obvious influence on operating parameters of heating ventilation and air conditioning (HVAC) system, which further affects occupants' thermal comfort and energy consumption. This pilot study proposes an occupant centric control (OCC) strategy for stratum ventilation (SV) to achieve demand control ventilation (DCV). Firstly, the computer vision sensing system and deep learning algorithm are used to detect the number of occupants in real time, and the accuracy of the number of occupants in the office environment was evaluated. Then, the occupant centric stratum ventilation control strategy is designed by the dynamic changes of cooling load. Finally, the thermal comfort and air quality of the thermal environment created by the OCC strategy were evaluated through subject experiment, and the energy consumption of the HVAC system was calculated in combination with the energy consumption simulation software. This study adjusts system setting values according to actual needs, so that the HVAC system responds to the dynamic changes of the indoor cooling load in real time, creating a comfortable and healthy indoor environment in an energy efficient manner.

1 Introduction

Relevant documents issued by the U.S. Department of Energy show that building energy consumption accounts for more than 40% of primary energy consumption, of which 28% and 14% are used for residential and commercial buildings, respectively [1]. Heating, ventilation and air conditioning (HVAC) systems account for 40% of the building's total energy consumption [2]. Occupant information can significantly affect HVAC operating conditions and system energy consumption [3]. Traditional HVAC control strategies fail to meet occupant requirements. For example, the current design project is to operate at the maximum occupancy rate of the space at all times, ignoring the actual occupancy rate of the space, and fix the fresh air supply ratio at a certain value, such as 15%-30%. As a result, unused or completely unoccupied space is regulated by the air conditioning system, resulting in rooms being under-conditioned or over-conditioned and potentially a large amount of wasted energy [4].

Demand-controlled ventilation (DCV) system that regulate fresh air ventilation based on the total number of space occupants can reduce HVAC energy by 10% to 15% compared to buildings that set ventilation rates based on maximum occupancy rate [5]. Occupant centric control (OCC) strategy is an energy-efficient air-conditioning system conditioning strategy that captures environmental parameters and human information from the building space, which can be fed into the HVAC system control system to improve energy efficiency without sacrificing occupant comfort [6].

Existing studies use various non-contact sensors to detect indoor occupying location, number of occupants and occupying activities [7]. Environmental sensors such as carbon dioxide sensors and temperature sensors provide only rough estimates of indoor occupancy, and their placement affects detection accuracy. Motion sensors such as PIR sensor, ultrasonic detector and pressure sensor are used to detect whether there are occupants [8], but they cannot be used to detect the number or location of occupants. With the development of sensor technology, radio frequency identification (RFID) sensors can determine the spatial coordinates of occupants [9], but each occupant must carry an RFID tag. The Wi-Fi sensor can identify mobile devices to detect the number of occupants [10], but the detection accuracy will be affected by the occupants' habits of using devices and living. Camera-based machine learning (ML) models can predict occupancy presence and occupant activity [11] with an accuracy range of 80% to 97%. However, occupant privacy, consumption cost, and computational complexity are the main reasons that limit the development of vision and new sensors.

Stratum ventilation (SV) system directly sends the air to the breathing area of the occupants, and the vertical temperature stratification phenomenon occurs in the room [12], which improves the air quality and realizes the building energy saving. Each air outlet is responsible for different indoor zones, which is beneficial to the partition adjustment of the office space.

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Therefore, this study adopts the air supply method of stratum ventilation, and proposes an OCC strategy based on computer vision to realize real-time adjustment of the operating conditions of the HVAC system based on indoor occupant information, and mainly solve the following three research problems:

1. In the office environment, computer vision technology detects the performance evaluation and optimization scheme of occupant number.

2. The HVAC system adopts the air supply method of stratum ventilation, and the design scheme of real-time adjustment according to occupant information is embodied in the automatic control scheme of the HVAC equipment.

3. Comprehensive performance of OCC strategies: energy saving efficiency, thermal comfort vote (TCV), thermal sensation vote (TSV), perceived air quality.

2 Methodology

2.1 Occupancy counting method

Deep learning is an important branch of machine learning. The deep learning technology most closely related to computers is convolutional neural network (CNN). Its applications in the field of computer vision include image classification, object detection, face recognition, image search, image segmentation, video recognition, image synthesis and other applications. This research adopts the occupant detection algorithm based on CNN. The object detection architecture is divided into two types, one-stage and two-stage. One-stage directly generates positions and categories from images, while two-stage generates positions and categories through network, namely region proposal process. Both R-CNN and Faster R-CNN are object detection methods based on region proposal. The YOLO algorithm processes the entire image and converts the object detection problem into a simple regression problem. There is no region proposal and no separate calculating each region of interest (ROI), using GPU parallel processing to calculate the response map, the detection accuracy and detection speed are greatly improved [13].

In recent years, a large number of researchers have used the YOLO algorithm to detect occupancy in buildings, and the detection accuracy is between 80% and 97%. The HVAC system requires accurate occupant information and cannot adjust the air handling unit frequently. Therefore, the YOLOv5s algorithm is selected and the COCO dataset is used to train the weight parameters. The detection algorithm process is shown in Figure 1.

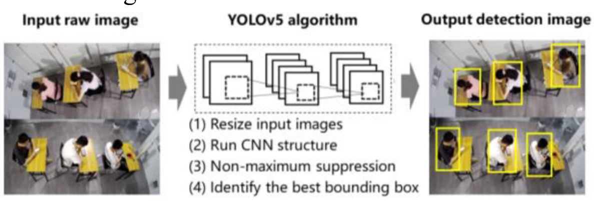

Fig. 1. The process of occupant detection algorithm.

2.2 Occupant centric stratum ventilation control strategy

2.2.1 Stratum ventilation (SV)

The SV provides fresh air at the head (breathing) level and generates a sandwich airflow field in an indoor environment, as shown in Figure 2.

Researchers measure the thermal comfort of the occupants through subject experiments [14], and evaluate the effect of the airflow field through objective measurements [15]. The experimental results show that: 1. The thermal neutral temperature exceeds 27 °C; 2. Thermal comfort index (PMV, PPD and PD) meet the requirements of ISO 7730, CR 175-1998 and ASHRAE 55-2020; 3. The ventilation efficiency is greater than 1; 4. The CO_2 concentration in the occupied zone is usually lower than that in the upper zone.

Due to the above-mentioned characteristics of this airflow organization, it can save at least 25% and 44% of energy throughout the year compared with displacement ventilation and mixing ventilation [16]. Combined with the feature of SV that can be adjusted in zones according to the distribution of occupants, the OCC strategy based on stratum ventilation can realize demand-controlled ventilation thereby further realizing the energy saving of HVAC system.

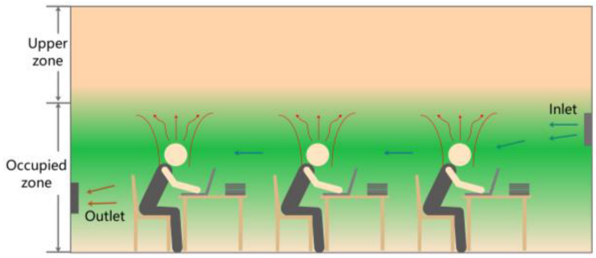

Fig. 2. Stratum ventilation airflow field diagram.

2.2.2 Demand-controlled ventilation (DCV)

The occupant centric control strategy adopts a closed-loop negative feedback control system, and the main control parameters are indoor temperature and system cooling capacity. During the operation of the air conditioner, the OCC strategy makes the indoor temperature fluctuate within a certain range (27±0.5°C), and the cooling capacity of the system meets the requirements of the indoor dynamic cooling load.

This study is aimed at two types of air-conditioning systems, the first is primary return air, constant air volume system, and the second is all fresh air, variable air volume system. The cooling capacity of the former period is Q_0, the variation of total cooling load caused by occupant change is △Q, see formula (4), and the given cooling capacity of the current period is Q, see formula (5).

$$Q_H = n \times \varphi \times (q_1 \times X + q_2) \tag{1}$$

$$Q_F = 1.393 \times 10^5 \times n \times (h_w - h_o) \tag{2}$$

$$Q_T = Q_H + Q_F + Q_E \tag{3}$$

$$\Delta Q = \Delta Q_T = \Delta Q_H + \Delta Q_F = \Delta n \times \varphi \times (q_1 \times X + q_2) + 1.393 \times 10^5 \times \Delta n \times (h_w - h_o) \quad (4)$$

$$Q = Q_0 + \Delta Q \quad (5)$$

where, Q_H is the total heat load of the human body, n is the number of occupants, φ is the clustering coefficient, q_1 is the sensible heat load, X is the cooling load coefficient of the sensible heat dissipation of the human body, q_2 is the human latent heat load, Q_F is the fresh air cooling load, h_w is the outdoor air enthalpy, h_o is the supply air enthalpy, Q_T is the cooling capacity required by the air conditioning system, Q_E is the room cooling loads other than the total human heat load, Δn is the difference between the number of occupants in the former period and the current period.

Option 1: The fresh air volume and total cooling load vary with the number of occupants. The fresh air volume is adjusted by the air valve, and the supply air temperature is adjusted to provide the cooling capacity required by the current period, and realize the negative feedback adjustment of the cooling capacity.

Option 2: The total air volume and total cooling load vary with the number of occupants, and the total air volume is adjusted by the fan frequency to meet the cooling capacity required by the current period. The process of the air conditioning system control strategy is shown in Figure 3.

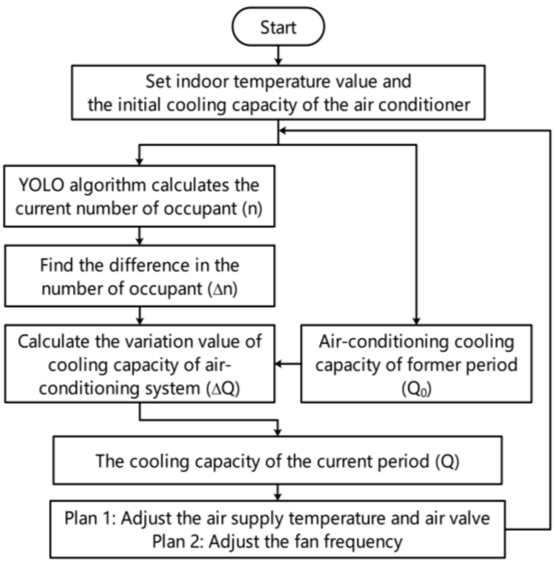

Fig. 3. The process of the air conditioning system control strategy.

3 Results and discussion

3.1 Occupant detection accuracy

In the chamber experiment process, two 1080P-pixel high-definition webcams were arranged to collect real-time indoor data on the number of occupants, and output the maximum number of occupants in this time period every 10 minutes. Finally, 170 video frames, 170 groups of detection data and 85 groups of occupant data were collected. The actual value is compared with the predicted value to test the performance of the occupancy detection method, as shown in Figure 4. In general, the trend of the actual value and the predicted value is similar. The average calculation result of the NRMSE value of the two cameras was 0.1913, and the detection accuracy was 83.09%.

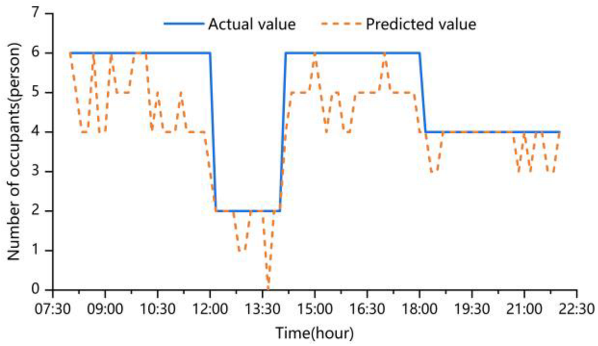

Fig. 4. A comparison of predicted and actual value.

From the cases of misjudgment, it can be seen that although the camera angle and number have been considered, it is difficult to completely avoid these mistakes because the person keeping the sitting position is the main feature of the office. Therefore, it is difficult to completely avoid these mistakes. This is the limitation of the YOLO algorithm, which has poor accuracy when detecting small area objects. A multi-camera system is a solution where each camera monitors a range of space and then aggregates the counts from multiple cameras.

3.2 Thermal environment evaluations

The experimental results of subjects show that the proportion of people who vote for thermal comfort from just comfortable just uncomfortable to very comfortable is "80%~100%", and the thermal environment reaches the acceptable standard.

The indoor perceived air quality of subjects was between "neutral to acceptable", which could ensure the inhaled air quality of occupants. According to the ASHRAE 55 standard, the two demand-controlled ventilation strategies both meet the requirements of occupants for indoor thermal environment comfort and air quality, and are suitable for the OCC strategies of stratum ventilation system in office environment.

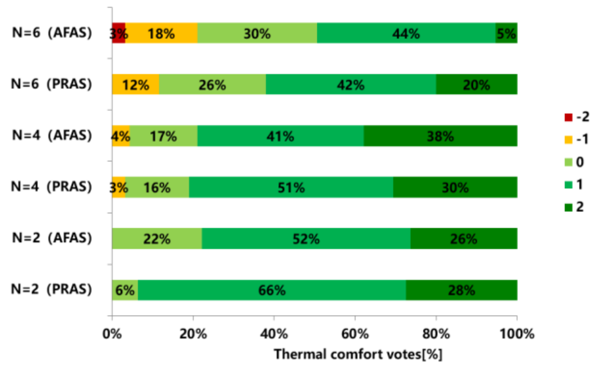

Fig. 5. Thermal comfort votes of subjects.

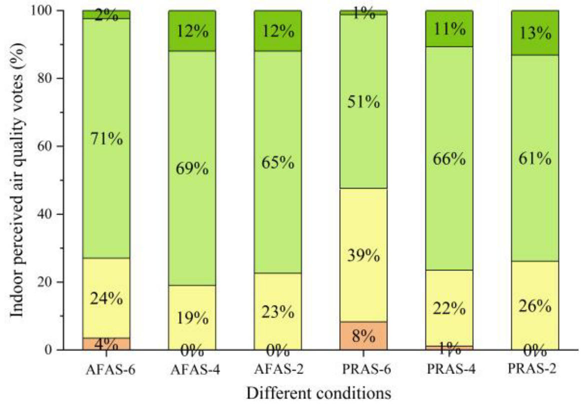

Fig. 6. Indoor perceived air quality votes of subjects.

3.3 System energy saving performance

The data of the system energy consumption analysis comes from the Energy-Plus energy consumption simulation software, and the on-demand ventilation system is designed according to the typical work schedule of the occupants, and compared with the traditional ventilation and air conditioning system. The calculation results show that the power consumption of all fresh air system equipment can be reduced by 5.26%, and the power consumption of the primary return air system equipment can be reduced by 22.47%. Therefore, this study has a significant system energy saving effect.

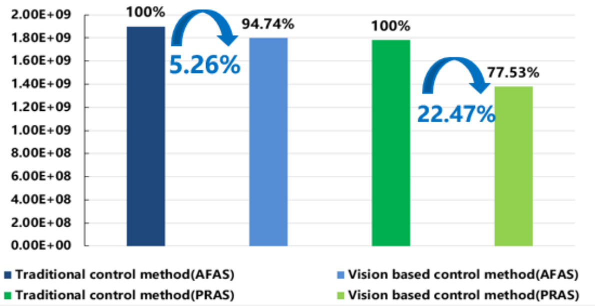

Fig. 7. Simulated total electricity consumption for a typical cooling month.

4 Conclusions

This study discusses three issues related to demand-controlled strategies of stratum ventilation, and evaluates occupant detection performance, system energy efficiency, and occupant thermal comfort through chamber experiment and energy simulation software. The experimental results can be summarized into the following conclusions: (1) The accuracy rate of occupant detection is 83.09%. It can be seen from the mis-judgment cases that the mis-judgment rate of detecting small-area objects is relatively high. Therefore, the occupancy detection method used in this study is suitable for a small office with multiple camera systems. (2) From the voting results of the subjects, it can be seen that this study meets the actual needs of occupants and can meet the thermal comfort and inhaled air quality of different occupants. (3) The power consumption of all fresh air system equipment can be reduced by 5.26% annually, and the power consumption of the primary return air system equipment can be reduced by 22.47% annually.

This research has certain limitations, which are manifested in the difference between the laboratory research and the actual working environment. In the future, the OCC model can be continuously optimized according to the historical data of occupant thermal comfort in the actual scene, and a system regulation strategy that is closer to the actual scene can be designed. This study provides insights into how ventilation and air conditioning systems respond to dynamic changes in indoor occupancy in order to minimize system energy consumption and improve human thermal comfort.

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