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# Demand-driven HVAC Control in Large Space based on Occupancy Distribution Detection through Indoor Positioning Systems

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## Abstract

*Office buildings represent the typically more intensive energy consuming parts and utilize substantial amount of energy in support of building services to satisfy occupants' comfort needs. This proves office occupant-driven demand control strategies, which have huge potential to improve energy efficiency in office buildings. In the large-scale rooms, uneven load distribution likely exists related to different occupancy pattern. The application of indoor positioning system in buildings, especially in the control of occupancy pattern, is one new relatively scientific and precis method, which has been demonstrated. This paper proposes one occupancy demand-driven control for air-conditioning systems in the large-scale rooms based on indoor positioning system that aims to deal with the problem of inaccurate occupancy detection and improve thermal comfort control. And proposed methodology will focus on the amount and approximate location of occupants by dual-network of Wi-Fi and BLE to study energy saving potential. The office room in the case is divided into a number of small zones with an independent variable air volume box and wireless sensor nodes installed at breathing level. The relationship between cooling load variation and occupancy pattern is estimated, furthermore, the comparison results on temperature distribution and energy-saving between different methodologies using computational fluid dynamics (CFD) simulation are presented.*

**Keywords – occupancy pattern; demand-based control; indoor positioning system; energy efficiency**

## 1. Introduction

Building sector has been commonly identified as one of the largest energy consumers in all energy consuming sectors, which accounts for the most significant percentage of a country's energy consumption. [1] Office

buildings commonly are more intensive compare to residential buildings because of HVAC systems. In the large-scale rooms equipped with high height and large floor area, suitable and sufficient building service quality is extremely important. In a typical commercial building, it is not uncommon to find such large-scale spaces partially occupied or unoccupied but HVAC system runs at full capacity. [2][3] In addition, because of uneven occupancy distribution, thermal comfort may be deteriorated when some zones may be over-cooled and some zones may be sub-cooled. Under these conditions, energy could be significantly wasted. Therefore, it is necessary to implement an efficient and high-quality operating model for the HVAC system. [4] In order to improve the energy efficiency and control performance, load uneven distribution must be considered. [5] And demand-driven control is ideally and commonly applied to improve HVAC systems control accuracy and avoid unnecessary wastes by actual occupancy pattern rather than rigid parameter setting. Many simulation-based researches show that potential energy saving from demand driven HVAC operations varies from 10% to 60%. [6][7]

In this way, Occupancy detection has caught increasing attention. [8][9][10] Some researchers perform building energy consumption analysis and prediction based on the ASHRAE recommended occupancy diversity factor from the historical occupancy information. [11] Other researchers apply occupancy sensors and conduct data-mining algorithms to derive the occupancy pattern from aggregated data. [12] Others tried to install temperature sensors to monitor temperature around breathing level so that occupancy is profiled by temperature fluctuation. In this research, we propose a way of occupancy acquisition based on the Indoor Positioning System with Wi-Fi and iBeacon to guide the facility control. [13] The indoor positioning system is capable of getting real-time location and identity of object. We applied the location information as the major indicator to quantify occupancy and developed efficient control mechanism to improve the HVAC system control. The adoption of this indoor positioning system can help to resolve the problem of inaccurate occupancy and uneven load distribution.

## **2. Methodology**

### **2.1 Model Introduction and Configuration**

The preliminary study takes a large-space office room as an example to explore the possibility of implementing demand-driven control mechanism based on high resolution occupancy information. Fluent Airpak was employed to simulate temperature distribution of airflow pattern under different control strategies. Length of the office room is 10m, width is 10m and height is 3m. There are 21 occupants working in the test space and each of them has one working desk, one computer and one monitor. The air in

this room is a steady and incompressible Newton fluid with the buoyancy effect of the body face neglected. The default ambient temperature is set as  $35^{\circ}\text{C}$ , which is a typical summer temperature in the subtropical region. [5] The specifications of the test room are illustrated in following Figure 1. The office also has wireless temperature sensors installed at human breathing level and at least 0.5 m away from the nearest occupant. [5] The walls of the room are adiabatic and the heat flux of the wall is neglected. The turbulence in the room is modeled with two standard  $k-\varepsilon$  equations to represent airflow of the mixing ventilation.

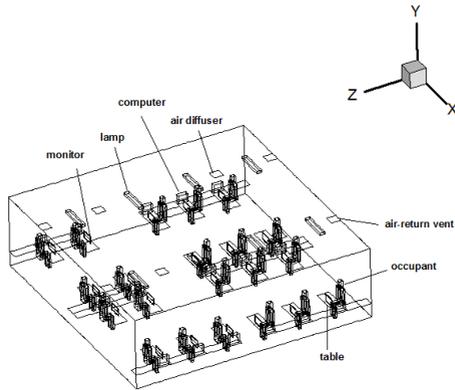


Fig. 1 the configuration of the office room

## 2.2 Infrastructure Coupling

The infrastructure setup of the proposed control strategy is shown in figure 2. Wireless temperature sensors are installed at the breathing level to measure temperature in the space as the validation. Wi-Fi access points (AP) and BLE broadcasters (iBeacon) are installed to construct the positioning coordination. In indoor positioning part, for each access point and iBeacon, indoor occupants can reach corresponding signal strength (dB) and based on  $k$ -NN algorithm, approximate location can be determined, which would not be discussed in this paper.

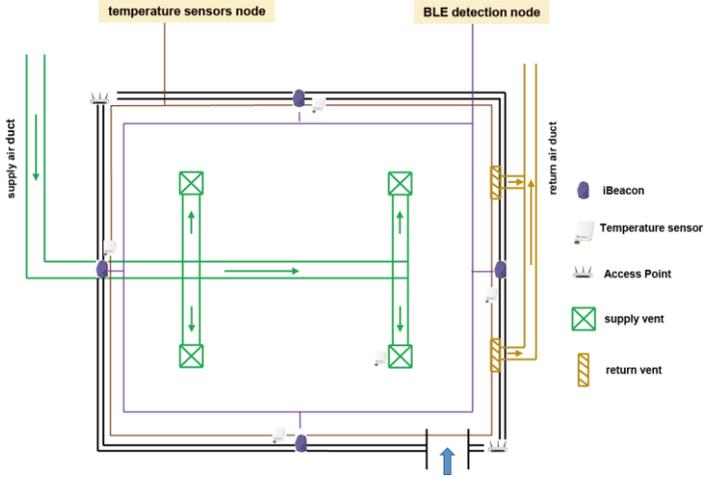


Fig. 2 infrastructure setup of the experimental space

Figure 3 shows the coupled relationship between occupancy detection system and HVAC control system. Through a positioning algorithm and received signal strength of all AP's and iBeacon's, the indoor positioning system is able to roughly locate the occupants inside the room. Identity of occupants also can be acquired through the device unique MAC Address or UUID. Then both the number of occupants and their distribution inside the room could be identified. And in room occupied pattern, cooling load estimation in each zone can be determined by detected occupancy pattern, which is used to control VAV box in corresponding zone based on demand-driven adjustment. Occupants are the control object and thermal comfort would be determined by temperature sensors node detection.

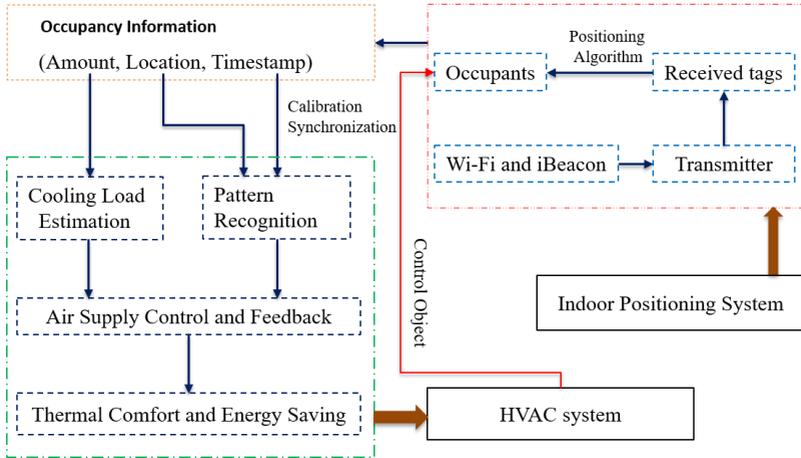


Fig. 3 Coupled indoor positioning system and HVAC system

### 2.3 Control Algorithm

We divided the room model into four independent zones (zone A, zone B, zone C and zone D) as in figure 4. Each zone is divided into even smaller patches for higher error tolerance in positioning. The temperature of each zone is collected from the wireless temperature sensors that installed in each zone and temperature represents the comfort level of occupants.

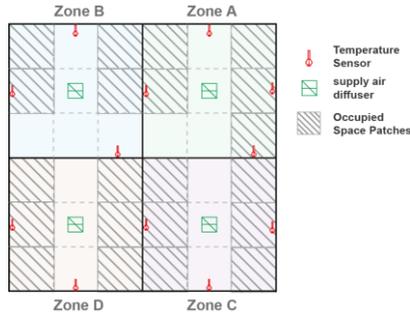


Fig. 4 simplification of office room in the case study

The flow chart in Figure 5 illustrates the demand-driven control algorithm embed with occupancy inputs. The initial parameter setting for the system related to HVAC operation, such as the supply temperature, room temperature and etc., are determined based on the thermal equations. The cooling load in each zone would be estimated by transfer function

method (TFM). [14] At first, the indoor positioning system will identify if zones or patches are occupied or not. No cooling air is supplied once one zone is detected with unoccupied situation. While secondly if occupied, then based on the populations in a zone, the cooling load can be estimated and used to update the operation of air conditioners. In occupied zones, the VAV box will switch on the air conditioner based on estimated load. PID control and feedback mechanism will adjust the air flow rate to reach the setting point until the environmental temperature reaches the necessary level. When a VAV box of an occupied zone is fully operated for a specified time period and the corresponding representative temperature hasn't been reached to the setting point, a VAV box from the adjacent zone area will be turned on to provide more cooling air to compensate the necessary cooling load. And two zones would be conditioned together with corresponding VAV boxes until the set points in two zones. At last, once the thermal condition reaches the sufficient level and occupancy changes in previous zone, the VAV box of adjacent zone will be turned off first.

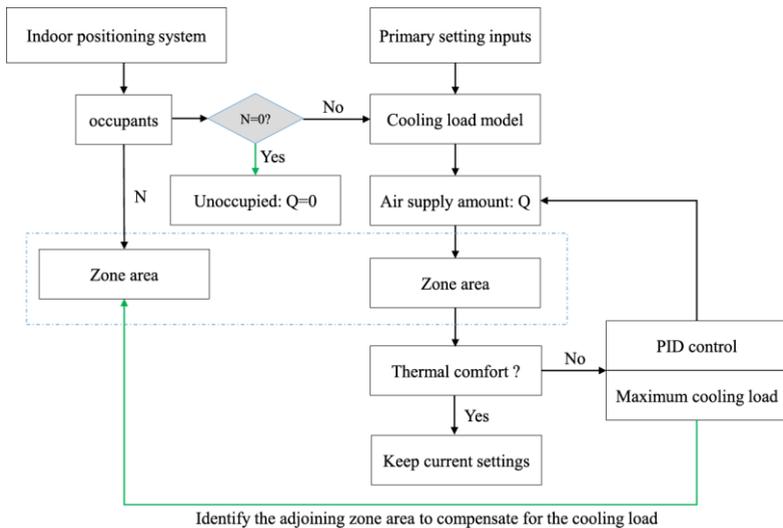


Fig. 5 proposed integration of supervised control algorithm for operation

Comparing to conventional control system, the proposed algorithm encourage parallel control for each zone based on high resolution occupancy information. The energy saving relies on matching the demand and capacity and avoiding unnecessary cooling or heating activities for unoccupied zones. The proposed system is especially suitable for the indoor space with uneven load distribution.

### 3. Results and discussions

The preliminary experiment includes 6 scenarios with four zone occupancy types: (1) fully-occupied - residents occupy all patches, (2) half-occupied - more than or equal half of patches in a zone are occupied, (3) partial-occupied - occupied patches less than half of total number of patches and (4) unoccupied - zones without any resident. Also another two types of occupancy distributions are defined as even distribution, in which all four zones are occupied more or less, and uneven distribution, in which some zones are unoccupied. Table 1 shows the some cases about those different types.

Table 1. Occupancy information and supply air amount in twelve scenarios with four zone occupancy types

INDEX	Zone A	Zone B	Zone C	Zone D	Total	QA	QB	QC	QD	Total	Occupancy
						(m <sup>3</sup> /h)					
01	5	4	6	6	21	353	265	382	382	1382	fully-occupied pattern
02	5	0	6	6	17	353	0	382	382	1117	uneven-occupied pattern
03	5	4	6	0	15	353	265	382	0	1000	uneven-occupied pattern
04	0	0	6	6	12	0	0	382	382	764	uneven-occupied pattern
05	5	4	0	0	9	294	206	0	0	500	uneven-occupied pattern
06	0	0	0	6	6	0	0	0	265	265	uneven-occupied pattern

Note: : NA means the number of occupants in zone A

QA means the supply air amount of VAV box in zone A

In the demand driven control mechanism, the indoor positioning system can distinguish if the zone is unoccupied or not and the VAV box is switched off if no occupant is located in the zone. When the zone is occupied with some occupants and the VAV box in this zone will be adjusted based on the actual demand and temperature sensors, especially the temperature sensors near the occupants. In the following test, proposed control methodology was compared with some conventional control methodologies. Conventional control system uses a single thermostat to synchronously control all VAV boxes according to differential between

measured temperature at the return air head duct and room temperature set point and temperature distribution in this methodology is showed in the right of figure 6. Or temperature sensors at the occupied level is used to detect if the zone is occupied and it would saving cooling air flow rate when temperature at breathing level is kept around thermal comfort level. Temperature around return duct level is ignored and over-cooling is avoided compared to conventional methodology. Temperature distribution is showed as the middle of figure 6. When proposed control methodology is implemented, VAV boxes are only switched on at the occupied zones and unoccupied zones would be not conditioned by supply air.

It is more appropriate to define the unoccupied zone based on occupant number than indoor temperature. For half-occupied patterns, taking scenario 4 as an example, assuming there are no occupants in zone A and zone B and equipment is on in all zones. The required supply air flow rate by proposed methodology is 940 m<sup>3</sup>/h to maintain the temperature of occupied zones (zone C and zone D) around 25.5°C. Since supply air is only conditioned into occupied zone, zone A and B would be ignored with no cooling air, which caused that zone C and D reached required temperature setting while temperature in zone C and D would be higher. For supply air flow rate adjustment based on temperature wireless sensors, zone A and zone B still need cooling air to be conditioned into setting point, meanwhile zone C and D is also conditioned. The required supply air flow rate is 1087 m<sup>3</sup>/h to maintain temperature in all four zones around 25.5°C. Conventional control methodology required supply air flow rate is 1350 m<sup>3</sup>/h to maintain return air temperature around 25.5°C while temperature under occupied level is around 24.6°C, which caused thermal comfort around occupancy level would be not under required level while energy would be wasted. Comparing with the two control methodologies, the proposed demand driven approach has a flow rate of 147 m<sup>3</sup>/h and 410 m<sup>3</sup>/h, which saves 13.5% and 30.4% of energy consumption.

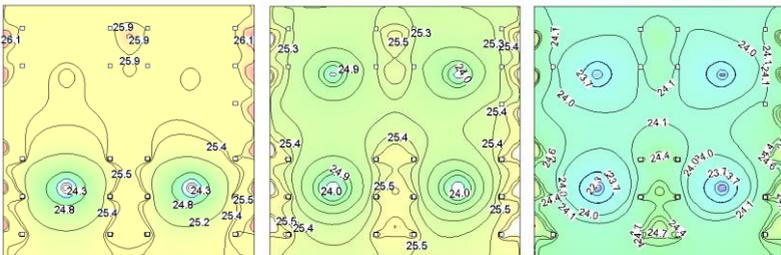


Fig. 6 Temperature distribution at occupied level when using proposed control (left), temperature distribution at occupied level when based on temperature (middle) and temperature distribution at occupied level when using conventional control (right)

When equipment, which can cause fluctuation of temperature, demand-driven control method can perform better than occupancy detection based on temperature sensor nodes. The more energy consumption results from the temperature fluctuation that not caused by occupants. Therefore, indoor positioning systems possess a huge advantage on its single focus on occupants.

#### 4. Conclusion

In this paper, we intent to optimize cooling air supply efficiency in HVAC systems to avoid the air cooling load uneven distribution and improve the control accuracy. Occupancy pattern is key to cooling load estimation and control methodology. In the proposed methodology, indoor positioning system is the critical tool to detect occupancy pattern. VAV boxes in zones are independently controlled and each VAV box can be adjusted based on actual demand in each zone. Based on such methodology, the space will be conditioned refer to actual demand. Simulation results show air supply rate varies with occupancy pattern and there is a great energy-saving potential when demand-driven HVAC operation is applied. Then energy conservation can be achieved and thermal comfort of occupants are also guaranteed.

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