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Review of occupancy sensing systems and occupancy modeling methodologies for the application in institutional buildings

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ABSTRACT

Occupancy information in a building is critical in terms of indoor environmental quality, energy consumption and building energy simulation. However, it is not easy to gather and model the occupancy information. Within the framework of institutional buildings, the large occupancy number and the very high occupancy variation will pose a higher challenging for occupancy number counting and modeling. This review paper reviewed the techniques and modeling methodologies in buildings and listed the pros and cons for further consideration for the application in institutional buildings.

1. Introduction

1.1. Occupancy has great impact on building energy consumption as well as the indoor environmental performance

Occupancy information constitute one of the critical building information both in terms of energy consumption and the indoor environmental quality. The presence of occupants will release both sensible and latent heat to the indoor spaces and the occupants' behavior such as the operation of windows, turning on/off lights and fans will also influence the indoor loads. Azar and Menassa [1] found that the building energy consumption is highly sensitive to occupancy-related behavioral parameters. Yang and Becerik-Gerber [2] further investigated the use of HVAC schedules observation-based personalized occupancy profiles in a three-storey office building and found that up to 9% energy can be saved compared to the conventional default schedules. Mahdavi [3] stated the importance of occupant behavior modeling in the field of occupancy based controls. Studies focused on the occupancy behavior modeling and associated energy saving have been applied in different areas of buildings, such as air-conditioning [4], ventilation [5], and lighting [6]. Results have shown that a typical 30% energy savings can be achieved with occupancy sensors to control lighting [7]. 30% cooling energy reduction can be achieved by using occupancy control in an open office [8] by having the thermostat setting of the unoccupied zone higher than that of the occupied zones.

Increased awareness of the indoor environment quality associated health and productivity issue in buildings has been a must have feature of buildings to consider the indoor environment quality while focusing on energy saving. Occupant, generate heat as well as CO_2 into the indoor environment, will also influence the indoor environment such as CO_2 concentration, door status, light level, binary motion, and temperature [2].

1.2. Occupancy numbers and patterns are the basis and key input of building simulation tools

In addition, occupancy numbers and patterns are the basis and key input of building simulation tools, such as Energy Plus [9], ESP-r [10], DeST [11,12], and TRNSYS [13]. These simulation tools are able to generate energy consumption profiles of cooling, heating, lighting systems, etc. Hence they are helpful in terms of system or whole building energy performance analysis. If an accurate occupancy dynamics can be used as input, then, accurate forecasting of building energy usage can be achieved [14–17]. Yang and Becerik-Gerber [2] evaluates the personalized occupancy profiles acquired through three methods: time-series modeling, pattern recognition modeling and stochastic process modeling. The results shows the impact of implementing the three personalized occupancy profiles on energy simulation results outperform the fixed design profiles.

Furthermore, a lot of studies have looked at the high energy consumption and the discrepancy of actual consumption with predicted value. Study [1] found that the actual consumption was

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about 85% higher than predicted value in university campuses buildings. Studies by Staats et al. [18] and Webber et al. [19] indicated that more than 50% of the total building energy is consumed during the non-working hours mainly due to additional occupancy or occupancy behavior. Meier [20] showed the similar finding that much higher energy consumption happened due to the additional equipment and longer lighting hours and can be reduced through occupancy behavioral changes. Masoso and Grobler [21] further supported above findings.

However, the occupant behavior varies significantly according to individuals. The indoor air thermostat setting points varies from below 19 °C to above 25 °C in residences in Kuwaiti [22] which leads to a very different cooling load consumption case by case. Hong and Lin [23] simulated a typical single-occupancy office room. They found that the wasteful work style consumes up to 90% more energy compared to the standard or typical work style. The energy audit study [21] on six randomly selected commercial buildings in South Africa found that more than half of the energy is used during non-working hours than during working hours, with about 19–28% of the building energy having gone to the unoccupied hours of the weekends. The findings from Zhao et al. [24] also suggested a 36.67–50.53% discrepancy between the "prototype" weekday occupancy schedule and the real learned schedule in this particular office, which lead to a discrepancy between the real and simulated energy consumption.

2. Occupant number and pattern determination

The most basic and simple methodology used for occupancy information collection is questionnaire, together with interviews with key management person focuses on mapping the pattern of daily room activities and occupancy. Questionnaire study [25] found that 92% of the building users are visitors, which shows a highly possibility of occupancy variations in buildings. Aerts et al. [26] use the data from Time-Use Survey (TUS) and Household Budget Survey (HBS) [27] to achieve the combined surveyed occupancy data. The activities and movements from the occupancy were recorded with indicating if they were at home or if they were accompanied by someone. However, such survey and observational methods are labor- and time-intensive to gather, and may not accurately represent the actual occupancy patterns.

Another methods used to counting and localization the occupancy in indoor space is the occupancy sensors. These methods can be classified into two groups. The first group is using the technology based on radio frequency (RF) signals, which is developed on the basis of electromagnetic signal detections [28] A typical RF system consists of an antenna, a transceiver and a transponder. RF location sensing can be applied in either an active or passive mode. In the active location mode, the antenna is installed at the target location [29]. With passive RF tags supplying to the surrounding space, the coordinates of the object are then calculated based on the reference tag coordinates [30]. However, the application of this process must be in conjunction with a large number of reference tags. Hence, error may increase where the target is too far away from the tag or the target is surrounded by an insufficient number of reference tags. Despite the above mentioned technology, the passive mode, which will have the target location installed with an active RF tag [31] can be another option. Many studies have applied the RF including RADAR [32], SpotON [33], LANDMARC [34], and Ekahau [35] to occupancy counting and location study. Li et al. [36] also developed an occupant monitoring system based on an RFID and furthermore Liao et al. [37] proposed an agent-based method with graphical modeling for building occupancy. However, these methods might be significantly affected by indoor electricmagnetic conditions.

The third group is based on the information from infrared [38], ultrasound, or video cameras, and the accuracy may also not stable due to the environment changes [39]. These occupancy sensors detect activities in their coverage area and return a control signal that indicates occupancy status. The sensors from this group are installed at the main entrance of the targeted building/room and have been applied in many studies. One recent study by Gul and Patidar [25] is based on a bi-directional infrared beam to count people entering or leaving the building. By creating an invisible barrier of two parallel infrared beams across the entrance, the number of people entering or leaving can be counted through the number of interruption. Occupancy logs were adopted by Wang et al. [40] to study 35 single person offices at a large office building. With an infrared sensor placed behind a fresnel lens in each office, signals as an event "A vacant to occupied" will be received when the room is vacant and the sensor detects motion; signals as event "An occupied to vacant" will be received when there has been no motion for a 15 min interval that averaged. Studies also employ the building security cameras, doorway electronic counting sensors to report the occupancy diversity factors in educational buildings [41]. Duarte et al. [42] revealed occupancy patterns in an 11-story office building through the use of 629 pre-existing ceiling-mounted passive infrared occupancy sensors. The coverage area of the sensor in this study is about 24 ft in diameter with a 360° line-of-sight. The sensors do not count people but report the change of state and are designed to control light fixtures based on a predetermined time delay for that particular building.

Carbon dioxide (CO_2) sensors have been employed to estimate the number of occupants in the spaces for a long time [43,44]. As discussed earlier, occupancy is the CO_2 generator and the occupancy presence can be inferred through the CO_2 concentrate level. However, limitations such as the window or door positions, outdoor air supply rate, and the proximity of the occupants to the sensor have been reported. Uncertainties in the estimation errors, and second, latency of the CO_2 sensor responses (i.e. the aspect of time delay) are also part of the limitation when applying CO_2 sensor for occupancy number calculation [45].

Wang et al. [46] found a suitable algorithm with the exhaust CO_2 level as input. After implementing three versions of the direct approach based on the CO_2 level, the result showed high accuracy. Similar studies were also presented in study of Mumma [47], the CO_2 levels were measured in the room in the exhaust air, and the result showed fast estimations with accuracies of ± 2 people.

Latest development of information technology such as global positioning system (GPS), cellular data, wireless local area network (WLAN) and Bluetooth are also applied in the occupancy detecting and counting researches [39,48–50]. A relatively new option is the GPS location and Wi-Fi connection [51] which is suitable for buildings with multiple overlapping access points as the reference system for connection. However, the total number of Wi-Fi connections may not be accurate with the large building scale and a large number of occupancy for institutional buildings. Furthermore, somewhat surprisingly, Hailemariam et al. [44] reported that inclusion of other sensor types beyond motion sensors did not improve overall occupancy detection accuracy, indicating that the error propagating from different sensor types can undermine the accuracy of occupancy detections.

As a summery, the main benefits and drawbacks of the above techniques are listed in Table 1.

3. Stochastic nature of occupant behavior and variability of occupancy numbers

Since the energy consumption of the building is highly related to the occupant's behavior [52,53], the way how we will save energy should start with looking at the occupants' behavior. The way the occupant switch on or switch off the lights or other devices when