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A knowledge based approach for selecting energy-aware and comfort-driven HVAC temperature set points

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ABSTRACT

HVAC systems are responsible for providing acceptable thermal conditions and indoor air quality for building occupants. Increasing thermal comfort and reducing HVAC related energy consumption are often seen as conflicting goals. Few researchers have investigated the feasibility of reducing HVAC related energy consumption by integrating occupants' personalized thermal comfort preferences into the HVAC control logic. In this study, we introduce a knowledge-based approach for improving HVAC system operations through coupling personalized thermal comfort preferences and energy consumption patterns. In our approach, thermal comfort preferences are learned online and then modeled as zone level personalized comfort profiles. Zone temperature set points are then selected through solving an optimization problem for energy, with comfort, indoor air quality, and system performance constraints taken into consideration. In the case that acceptable comfort levels for all occupants of a zone were not achievable, the approach selects set points that minimize the overall thermal discomfort level. Compared to an operational strategy focusing on comfort only, evaluation of our approach, which aims for both maintaining or improving comfort and reducing energy consumption, showed improvements by reducing average daily airflows for about 57.6 m^3/h (12.08%) in three target zones.

1. Introduction

Thermal comfort is one of the most influential factors affecting a building's indoor environmental quality [1]. Parameters influencing thermal comfort can be divided into two categories: environment related parameters (e.g., air temperature, humidity) and occupant related parameters (e.g., clothing level, metabolic rate) [2]. Since occupant related parameters are difficult to be measured frequently and in real-time, building management systems (BMS) are usually operated based on generalized recommendations offered by the standards, such as the ASHRAE Standard 55 (Thermal Environmental Conditions for Human Occupancy) [3] for thermal comfort and ASHRAE Standard 62.1 (Ventilation for Acceptable Indoor Air Quality) for air quality requirements [4]. Thermal comfort standards provide comfort models, which estimate occupants' thermal satisfaction levels based on the environment related and occupant related parameters, measured through controlled experiments. However, lack of information about the actual occupant related parameters often results in conservative HVAC operational settings. Moreover, majority of the HVAC system controllers work with single temperature control loop [5], therefore they cannot comply with the standards' recommendations effectively as these models require sensing several controlling parameters (e.g., humidity, airflow speed, and clothing level). Commercial buildings in the United States consume about 20% of the total energy, 43% of which is consumed by HVAC systems [6]. This significant share demonstrates the importance of investigating efficient HVAC operational strategies that work with existing HVAC systems. It is interesting to note that it had been shown that 7 to 15% of HVAC related energy consumption could be saved by increasing the temperature set point by 1 °C in warm seasons in three large cities (i.e., San Francisco, Phoenix and Miami) in the United States [7].

Several research efforts have tried to address the need for extracting personalized thermal comfort information for individual occupants to enable more efficient HVAC operations [8–13]. These efforts use questionnaires, field surveys, or physiological measurements and they determine individuals' comfort levels, while standards' comfort models do not differentiate between different individuals' needs under similar conditions [14]. Some of the methods used in the above-mentioned efforts could be time consuming, intrusive for occupants, and require installing further controlling

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infrastructure to work with legacy HVAC systems. These efforts aim to provide the most comfortable conditions for the occupants. However, previous research proved that humans experience comfort in a range of environmental conditions [15]. If energy consumption requirements for maintaining personalized and comfortable environmental conditions are understood, HVAC systems could be operated based on not only the personalized comfort information but also based on the energy consequences of different comfort settings.

In our previous studies, we developed a framework that uses a participatory sensing approach for human building interaction for thermal comfort (HBI-TC) [16]. In the HBI-TC framework, occupants' thermal comfort information is learned and modeled as comfort profiles. These profiles present different sensations over a range of room temperatures and are developed using a fuzzy pattern recognition algorithm. The framework interprets occupants' comfort profiles and calculates personalized preferred temperatures (if there is a change in preferences, updates the preferred temperatures over time), and operates the HVAC system using a complementary control algorithm, to minimize the average error between the preferred and actual temperatures in rooms of a zone. This framework was implemented in a test bed and promising results from both comfort and energy perspectives were realized and reported in [17]. However, personalized thermal comfort profiles could also be used to generate a range of environment temperatures where comfort is maintained. Understanding the energy consumption requirements for providing different ranges of indoor temperatures and integrating this information into the HVAC system control loop could potentially be used to select set points, which improve the occupants' overall comfort levels and also increase the energy efficiency of HVAC systems while using existing HVAC controllers in buildings.

In this paper, a knowledge based approach for selecting HVAC set points is introduced by taking into account energy consequences, indoor air quality requirements (i.e., minimum air flow rates and quality driven from ASHRAE Standard 62.1), and occupants' comfort constraints. The approach determines HVAC system set points through solving an optimization problem for HVAC energy usage performance metric (i.e., air flow rates) at the zone level on a daily basis. The structure of the paper is as follows. In Section 2, a review of recent studies that focus on selection of comfort-driven and energy-aware operational strategies is presented. In Section 3, a detailed description of the HBI-TC framework is provided and potential improvement areas are discussed. In Section 4, the methodology for enabling the integration of comfort and energy information is provided. Information about the test bed building and occupants is presented in Section 5. Section 6 presents the validation results and the comfort and energy consequences of the proposed approach. Limitations of the work are presented in Section 7. Finally, conclusions are presented in Section 8.

2. Comfort-driven and energy-aware HVAC operations

There are several research efforts, which aimed to improve HVAC systems' energy efficiency, occupants' thermal comfort, and indoor environmental air quality [18,19]. Thermal comfort driven HVAC operations often use the PMV (predicted mean vote) model [20] as a metric for measuring occupants' thermal comfort. The PMV model is also adopted by several standards such as the ASHRAE 55 [3] and has been extensively used by the industry for determining acceptable thermal conditions in indoor environments [5,21,22]. The PMV model uses a number of environment related parameters (e.g., temperature, humidity) and occupant related parameters (e.g., clothing level) and calculates occupants' average thermal sensations.

Various operational strategies have been used to optimize HVAC energy consumption by utilizing the PMV model for comfort constraints. Some of these operational strategies [23,24], complementary to the existing HVAC control logics, influence the performance of HVAC systems by adjusting set points [25], while other operational strategies intervene existing HVAC control logics. Examples of approaches used in latter category are fuzzy controllers [26], neural network based controllers [27], and genetic algorithm based controllers [28]. Nowak et al. compared few control strategies, such as the dynamic matrix control (DMC) and generalized predictive control (GPC), using a simulation tool for minimizing energy consumption, while maintaining PMV values in an acceptable range (between −0.5 and 0.5 on the PMV index) [29]. Freire et al. [5] proposed two strategies based on the PMV model, one only for comfort and one for both energy and comfort. The latter uses model based predictive control laws for minimizing energy usage, while maintaining acceptable thermal comfort levels. Simulation results from their studies showed that saving energy, while maintaining thermal comfort, is possible. Ferreira et al. [30] proposed a neural network based control strategy and created a simulation model using actual buildings' settings and their results showed that application of their proposed approach could maintain thermal comfort while saving more than 50% of energy consumption. Fong et al. [31] developed a heuristic approach by simulation coupling and proved that their proposed approach could reduce energy consumption by about 7% through adjusting operational settings for the chilled water and supply air temperatures system, while maintaining acceptable thermal comfort levels.

Although researchers have extensively used the PMV model for thermal comfort, the PMV model has a number of downfalls, including its inability to consider behavioral variations and the ability of humans to adapt to thermal environments [32]. Moreover, in order to implement the PMV model, several parameters have to be collected from an environment and from occupants in real time, requiring sensing infrastructure, which could be expensive and complex to be deployed in existing buildings [22]. Recently, to address these challenges, researchers have proposed personalized and real-time comfort sensing approaches, which can potentially be used in existing buildings [8–12,17,33]. These approaches aimed to estimate and model individuals' comfort levels separately in order to enable personalized comfort driven HVAC operations. Erickson and Cerpa [8] used a participatory approach for controlling temperature of rooms and showed all occupants were satisfied while energy consumption was reduced by 10.1% compared to the existing building control system. Murakami et al. [12] proposed an approach, which calculated daily set points through a collective voting by a group of 50 occupants in an open office space and adjusted HVAC set points. The results showed 20% energy savings compared to a constant set point (26 °C). Feldmeier and Paradiso [9] measured various parameters directly on the occupants' bodies to understand occupants' thermal comfort levels. They then used a PI (proportional-integral) controller to adjust HVAC system set points and also adjusted the window locations in their test bed buildings based on personalized comfort preferences, and realized 24% energy savings compared to the standard HVAC control system. These efforts aimed to provide the most comfortable conditions for occupants. However, previous research has shown that humans perceive comfort in a range of environmental conditions [15], similar to the comfort zone in the PMV model (i.e., between −0.5 and 0.5 on the PMV index). If thermally acceptable set points are determined, the selection of set points can be performed based on other criteria, such as system efficiency and different energy consumption objectives.

In this paper, we use personalized thermal comfort profiles and HVAC energy consumption data for identifying occupants' thermal discomfort levels and energy consequences of different set