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Personalized thermal comfort inference using RGB video images for distributed HVAC control

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HIGHLIGHTS

- A framework of a ubiquitous thermal comfort assessment for energy-efficient HVAC.
- The framework infers human thermoregulation states using RGB video images.
- The framework draws on thermoregulation mechanisms and Eulerian video magnification.
- Subtle blood flow variations to facial skin due to thermoregulation are inferred.
- The feasibility was evaluated for 21 participants under low and high temperatures.

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ABSTRACT

HVAC systems account for more than 40% of energy consumption in buildings to provide satisfactory indoor environments for occupants. The integration of personalized thermal comfort in the operation of HVAC systems has been shown to be highly effective in enhancing energy efficiency of buildings. To this end, research efforts have proposed personalized thermal comfort assessment through voting (i.e., occupant feedback) and profiling as well as physiological response measurement. In this study, we have proposed a novel approach for enabling RGB video cameras as sensors for measuring personalized thermoregulation states – an indicator of thermal comfort. If their feasibility for thermoregulation state inference could be established, optical cameras provide a cost-effective and omnipresent solution for distributed measurement of thermal comfort and consequently control of HVAC systems for energy saving. Accordingly, we have proposed a framework that draws on the concepts of thermoregulation mechanisms in the human body as well as the Eulerian video magnification approach. The framework is composed of several components including face detection, skin pixels isolation, image magnification. And calculation of detection index to infer subtle blood flow variations to the facial skin surface (i.e., blood perfusion), which is due to thermoregulation adjustments. In order to minimize the impact of variable illumination condition and the ambient noise on the results, different combinations of methods for framework components were taken into account. The feasibility assessments were conducted through an experimental study with 21 participants under low (20 °C) and high (30 °C) temperatures. In total, 16 positive cases out of 18 statistically significant cases were observed resulting in 89% of success rate using the most promising combinations of the methods. The results demonstrate that the proposed framework could contribute to realization of a non-intrusive, cost-effective, and ubiquitous distributed thermal comfort assessment that has been proven critical in increasing energy efficiency of the HVAC system through distributed control feedback.

1. Introduction

Increasing energy efficiency in buildings, as the major consumer in the United States [1], is of critical importance in achieving sustainability goals in the built environment. Thermal conditioning in buildings account for 48% of annual energy consumption in the United States [2]. The control logic in buildings relies on measuring temperature variations in a thermal zone (i.e., sub-spaces in buildings with independent control units). This measurement represents the indoor thermal condition that is compared against a control set point - a quantity that is determined through thermal comfort indexing. The main objective of thermal conditioning is to provide and maintain occupants' health, comfort, and productivity in an indoor environment. Therefore, thermal comfort quantification is critical in determining the

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energy consumption demands in buildings [3–7]. Conventionally, thermal comfort is measured by using heat-budget models. These models look at the balance of the human heat budget to variable environmental and metabolic heat loads. This balance is controlled by an efficient (for healthy people) autonomous thermoregulatory system [8]. The most widely adopted heat-budget model is the PMV-PPD model [9] that was developed through comprehensive empirical studies in controlled environments. The model quantifies thermal comfort and the percentage of satisifed occupants through predictive mean vote (PMV) and predicted percentage of dissatisfied (PPD) indices, respectively.

Although the PMV-PPD model has been used as the main approach in thermal comfort quantification, studies have shown that it could result in underestimating or overestimating personalized thermal comfort [10,11]. Nonetheless, in the wake of difficulty of quantifying the driving factors of PMV-PPD model in operational stage, conservative operational set points are commonly considered for thermal conditioning operations, which consequently lead to inefficiency of building systems' energy consumption and serviceability. The heat budget models, coupled with temperature sensing in thermal zones comprise the control logic of the heating, ventilation, and air conditioning (HVAC) systems. Accordingly, the control logic relies on average thermal satisfaction of a group of occupants in thermal zones that is communicated to building systems through a single sensing point as a temperature set point. This configuration could result in inefficient communication and temperature distribution in thermal zones and consequently, inefficient energy consumption. In order to overcome these limitations, distributed thermal comfort measurement has been introduced as an alternative solution [12], in which, through a field demonstration, we have shown that integration of personalized thermal comfort into HVAC control logic, could result in considerable energy consumption reduction (~40% in the test bed). The ubiquity of smart and personalized computing devices and the wireless communication networks enabled the application of personalized metrics for thermal comfort assessment. Occupants' feedback for thermal comfort profile learning [12,13] as well as wearable sensors [14,15] for measuring ambient and physiological variables were among the main techniques that have been adopted for cyber-physical systems with an emphasis on human-centered control techniques.

As the effectiveness of the techniques for evaluating personalized thermal comfort increases, the intrusiveness of the methods could be increased. Moreover, specialized devices will be needed to improve the quality of thermal comfort quantification, which is a challenge for ubiquitous and pervasive measurements. This observation brought us to the question that whether we could leverage optical video images via computer webcams for thermal comfort quantification for control feedback. Building occupants (specifically in office/administrative buildings) commonly interact with personal computers with connected video devices, which provide a non-intrusive platform for thermal comfort assessment. The main question, therefore, is whether computers can quantify human thermal comfort through RGB video images. Although video image analysis has been previously used in medical applications [5], its application in thermal comfort assessment has not been explored. This paper describes our study, in which we leveraged the human body thermoregulation mechanism and the Eulerian video magnification algorithm to devise a framework for identification of human thermoregulation states and evaluate the feasibility of inferring these states through RGB video images. The assessments in this study have been made under the constraints of control loops for building energy management systems.

2. Thermal comfort management background

The main criterion in design and operation of air conditioning systems is to ensure that an acceptable indoor air condition is provided for the occupants. Provision of thermal comfort and ventilation under the constraints of procurement and operational costs (i.e. energy expenditure) of the HVAC systems have led to numerous research efforts in optimizing the operation of these systems. As an active research area in the past few decades [16–22], among the recent research efforts, several studies have focused on advanced control techniques to improve the operation of HVAC systems with comfort and energy objective functions. Advanced fuzzy logic controllers (e.g., [20]), metaheuristic optimization algorithms (e.g., [23]), and model predictive control (MPC) strategies (e.g., [24]) were proposed and evaluated for increased energy efficiency of HVAC systems. However, in these studies, PMV has been widely used as the metric for evaluating the thermal comfort of the users in the environment.

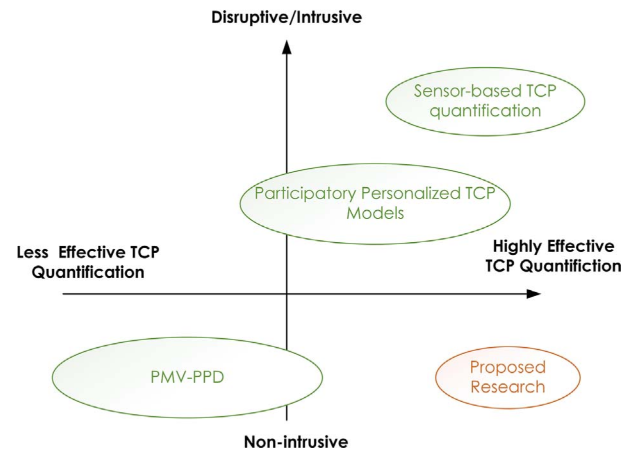

Fig. 1. Research spectrum of thermal comfort quantification.

Regardless of the control mechanism, the thermal comfort quantification is a critical component of energy management frameworks. Fig. 1 illustrates the comparative spectrum of techniques for quantification of thermal comfort that have been developed over the past few decades. As also reflected in the aforementioned studies, the PMV-PPD model is the most notable and commonly used thermal comfort quantification model. Although it is a completely non-intrusive approach, comparing the results of PMV-PPD model and occupants' reported thermal preferences shows the overestimating or underestimating of this model [25–27]. The main reason for this discrepancy is that the PMV-PDD model does not account for individual occupants' characteristics [10,11] and it uses a collective measure of thermal satisfaction through one sensing point (i.e., thermostat).

Estimating human factors including metabolic rates and clothing insulation is often difficult. Considering the importance of human related variables in accuracy of thermal comfort models [28], a wide range of research studies has been conducted to assess thermal perception for individuals. In general, these methods could be grouped into two categories as also depicted in Fig. 1. Methods in the first category directly ask occupants to express their thermal satisfaction through participatory data acquisition (i.e., occupant voting and profiling systems - OVPS). However, approaches in the second group seek to measure physiological variables and then obtain a correlation between these variables and thermal comfort perception (i.e., physiological sensing technologies – PST). In OVPS, participatory based solutions, in conventional form, include collecting feedback through surveys [29] or interviews [30] to understand occupants' perception. These methods are periodic and are mainly used to evaluate the performance of building energy management systems (BEMS) in case of complaints. To account for contextual dynamics (including occupants' dynamics and seasonal changes) and leverage occupants' adaptive capacity, personalized participatory sensing solutions (including our prior research [12,31,32]), were introduced to enable continuous sensing solutions for quantification of thermal comfort. In these approaches, ubiquitous devices such as smartphones [13,31,33,34] and personal computers [35,36] are employed to enable context-aware feedback from occupants