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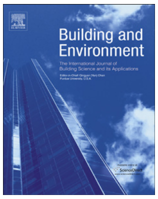

An online learning approach for quantifying personalized thermal comfort via adaptive stochastic modeling

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ABSTRACT

HVAC systems are the major energy consumers in commercial buildings in the United States. These systems are operated to provide comfortable thermal conditions for building occupants. The common practice of defining operational settings for HVAC systems is to use fixed set points, which assume occupants have static comfort requirements. However, thermal comfort has been shown to vary from person to person and also change over time due to climatic variations or acclimation. In this paper, we introduce an online learning approach for modeling and quantifying personalized thermal comfort. In this approach, we fit a probability distribution to each comfort condition (i.e., uncomfortably warm, comfortable, and uncomfortably cool) data set and define the overall comfort of an individual through combing these distributions in a Bayesian network. In order to identify comfort variations over time, Kolmogorov–Smirnov test is used on the joint probability distributions. In order to identify comfortable environmental conditions, a Bayesian optimal classifier is trained using online learning. In order to validate the approach, we collected data from 33 subjects, and an average accuracy of 70.14% and specificity of 76.74% were achieved. In practice, this approach could transform the comfort objectives to constrain functions and prevents pareto optimality problems.

1. Introduction

Commercial buildings are one of the largest energy consumers (18.9% of the total energy consumption), and greenhouse emission sources (18.89% of the CO_2 emissions, and 19.59% of the total greenhouse gas emissions) in the United States [1,2]. Heating, Ventilation, and Air Conditioning (HVAC) systems account for the largest share of the energy usage and gas emissions (43% of the commercial building energy consumption [1,2]). HVAC systems are primarily responsible for providing satisfactory thermal conditions and indoor air quality for building occupants. They are often operated based on the recommendations provided by the standards (e.g., ASHRAE Standard 55 (Thermal Environmental Conditions for Human Occupancy) [3] and ASHRAE Standard 62.1 (Ventilation for Acceptable Indoor Air Quality) [4]). Standards for thermal comfort conditions provide models, which estimate occupants' thermal sensations based on a few selected parameters (e.g., indoor air temperature, air humidity, clothing, etc.), which are measured through controlled experiments. Although more recent models (e.g., adaptive models) consider weather variations for estimating occupants' thermal sensations, they do not usually account for contextual factors (e.g., age, race, gender, etc.) that influence individuals' thermal comfort preferences. Thermal preferences vary from person to person, which suggests that a systematic procedure to quantify personalized preferences is needed [5]. In addition, many dynamic environmental and human related variables affect thermal comfort [6,7], and hence, individuals' thermal comfort ranges may change over time. This phenomenon requires models for personalized comfort models to be updated when new evidence is available (e.g., an occupant's perception of comfort or discomfort at a certain ambient condition is changed). Moreover, prior research proves that people perceive comfort in a range of environmental thermal conditions [8], which might provide an opportunity to save energy in buildings. Small thermal comfort related adjustments (e.g., adjusting the temperature set point by 1 °C) might have

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considerable impacts on the overall energy consumption [6]. In addition, it has been demonstrated that thermal comfort is the dominant factor influencing the overall satisfaction with indoor environments [9,10]. Therefore, context dependent approaches to model and estimate individuals' thermal comfort preferences that enable more efficient HVAC operations can potentially help energy conservation strategies. Reducing energy consumption and gas emissions through more efficient HVAC (eHVAC) systems and building automation and control systems (BACS) is emphasized in the recent report by Mitigation of Climate Change group at the Intergovernmental Panel on Climate Change (IPCC) [11]. These systems require understanding occupants' behavioral patterns as well as their personal needs.

Human Centered thermal Comfort Identification (HCCI) approaches aim to address the challenges of context dependency in thermal comfort by differentiating individuals and independently addressing individuals' states of comfort. These efforts could be divided into two categories: (1) survey based approaches; and (2) physiological measurement based approaches. Survey based approaches aim to understand the state of mind for thermal comfort by asking humans to fill a questionnaire, while physiological measurements based approaches aim to understand the state of humans' body for thermal comfort through certain physiological measurements (e.g., heart rate, skin temperature, etc. [12–18]). Thus, real-time monitoring of building occupants' thermal comfort through HCCI approaches requires continuous data acquisition. However, continuous data acquisition from building occupants is a challenging task, and therefore, is not widely used in daily building operations. In order to address this challenge, Human Centered thermal Comfort Modeling (HCCM) approaches correlate instant comfort levels (HCCI outputs) with some other variables, such as environmental related variables (e.g., indoor air temperatures, clothing levels) [17,18]. Thus, instead of continuous interactions with occupants (e.g., asking them to fill out a survey, taking physiological measurements), the selected correlated variables are used to estimate occupants' thermal comfort levels. Due to the difficulties and expense of monitoring all influential variables through a sensor network, and in order to achieve certainty in decision making, these models account for two categories of uncertainties [19]: (1) short-term comfort related uncertainties, caused by influence of variables, which cannot be monitored in real time on an individuals' comfort level, such as food intake, internal organs' health; and (2) long-term comfort related variations, caused by changes in weather or acclimation. From statistical point of view, short-term uncertainties result in a noise around a mean value, while long term uncertainties result in a shift in the mean value. Stochastic modeling, in contrast with deterministic modeling, integrates the above-mentioned uncertainties by defining degrees of beliefs (probabilities of occurrence) over the range of values that a decision should be made. The models used in standards (e.g., ASHRAE 55 – thermal environmental conditions for human occupancy [3]) cannot be categorized as HCCM approaches as they were built for a group of test subjects in a specific context (like in controlled experiments) and they are recommended to be used for occupants in other contexts. For example, PMV (predicted mean vote), as one of the most well-known models, is a statistical model that was created based on the results of the experiments conducted by Fanger in 60s [20]. The model maps few environment related parameters (e.g., indoor air temperature, indoor air humidity, etc.) to the PMV value of a group of occupants in an indoor environment [20]. In addition, the recently developed adaptive thermal comfort models [8,21] are also built based on correlation analyses between seasonal variations of environmental conditions and subjects' thermal responses, and they are not considered as personalized adaptive models.

In this paper, we introduce an adaptive stochastic modeling approach for modeling personalized thermal comfort of building occupants. Our adaptive model enables determination and quantification of both the short-term and long-term comfort uncertainties. Our stochastic models are probability distributions in a Bayesian network that feeds into a binary Bayesian optimal classifier. In order to detect long-term variations, we implemented a sliding window based algorithm that detects significant statistical differences in comfort votes. We compared our model with other standard classification techniques by applying these techniques (including ours) on the thermal comfort data collected from 33 test subjects in regular office environments. Individuals' thermal comfort levels were collected through a participatory sensing (survey based) approach described in Ref. [22].

We describe our approach and its validation in this paper. In Section 2, a review of recent studies on the Human Centered thermal Comfort Identification (HCCI) and Human Centered thermal Comfort Modeling (HCCM) is presented. In Section 3, we introduce our stochastic approach for modeling personalized thermal comfort, as well as the model update procedures. In Section 4, the test bed buildings and experimental design are explained. In Section 5, we present the results for stochastic model validation for short-term effects, and long-term comfort variations. Section 6 demonstrates the implementation of our approach in compliance with ASHRAE 55 (thermal environmental conditions for human occupancy) [3]. In Section 7, a discussion on implementation requirements and future work are provided. Section 8 summarizes the findings and concludes the paper.

2. Human centered thermal comfort identification and modeling

Human Centered thermal Comfort Identification (HCCI) has recently gained more attention due to (1) the inability of existing thermal comfort models to accurately estimate individuals' dynamic thermal preferences; and (2) the decreased cost of sensing infrastructure. HCCI approaches aim to understand individuals' states of comfort through direct measurements. These measurements record humans' perceptions or physiological responses to their thermal environments. Accordingly, two distinct categories of data acquisition approaches are used in literature: (1) survey based approaches, which try to quantify the perceptions; and (2) physiological measurement based approaches, which try to understand preferences based on physiological responses [17]. Survey based approaches require individuals to fill questionnaires about their thermal comfort levels. There are various questionnaire designs in literature with different scales, such as (1) the ASHRAE scale [3]; (2) the Bedford scale [23]; (3) the comfortable-uncomfortable scale [24]; (4) the Human Building Interaction framework for Thermal Comfort (HBI-TC) scale [25]. Due to their distinct designs, and subjective human understanding, scales should be carefully chosen and used based on the required application (e.g., Bedford scale unlike ASHRAE scale extracts information regarding thermal acceptability) [24,26]. Physiological measurement based approaches [12–17] are built upon the principle that physiological responses can be correlated with thermal discomfort. Therefore, monitoring the correlated measurements helps understanding when a subject is uncomfortable. If there was no evidence of thermal discomfort, these approaches reject the hypothesis that the subject is in a discomfort condition. However, there could be uncomfortable conditions (which is a state of mind [3]) that are not necessarily reflected in human physiological conditions [27]. Evidently, survey based approaches understand actual comfort levels more accurately than physiological approaches as they try to directly extract the state of mind of a person. In addition, the