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Thermal comfort modeling in transient conditions using real-time local body temperature extraction with a thermographic camera

Andrei Claudiu Cosma*, Rahul Simha

Department of Computer Science, School of Engineering and Applied Science, The George Washington University, Washington DC, USA

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ABSTRACT

This work evaluated the use of thermographic cameras as a non-invasive method to automatically model human thermal comfort in transient conditions, using data from 30 healthy subjects tested in an office setup with ambient temperatures between 21.11 °C and 27.78 °C. Office temperature, relative humidity, exposed skin temperature and clothing temperature were automatically measured over approximately 27 min per subject, using remote sensors and avoiding any contact with the subjects. Thermal comfort levels were evaluated using subjects feedback, recorded every minute for the entire experiment. Clothing insulation and metabolic rate were kept relatively constant for this experiment (0.54 clo and 1.1 met). Average skin temperature was extracted from five different locations, with average temperatures of 33.5 °C, 34.5 °C, and 35.6 °C corresponding to cold discomfort, comfort and warm discomfort respectively. Average clothing temperature was also extracted from three different location, with 32.3 °C, 33.8 °C and 35.0 °C corresponding to the same three comfort levels. Relative humidity levels were similar for all subjects, with average values between 38% and 33%. Results showed significant correlation between observed skin temperature, clothing temperature and thermal comfort level. Also, collected data showed that the temperature difference between different body locations was highly correlated with thermal comfort, and the variance of skin temperature over a small area was significantly correlated with thermal comfort. The results suggest that non-invasive thermographic cameras that combine visual and thermal modes are sufficiently accurate in real-world settings to drive control of HVAC systems.

1. Introduction

The increased demand for energy efficient buildings to reduce greenhouse gas emissions has pushed engineers to identify and address the issues with the main source of energy consumption within office and residential buildings. Based on the most recent CBECS [1] and RECS [2] reports, energy usage for residential and commercial buildings in the US represents 40% of the total energy used throughout the country. The same reports revealed that almost 50% of total energy used in homes and 33% of total energy used in commercial buildings came from heating, ventilation and air conditioning (HVAC) systems. That is a significant amount of energy consumed on a daily basis simply to provide physical comfort, and for which any possible reduction can have a significant impact on the total amount of energy used.

Traditionally, HVAC systems work on a setpoint temperature computed using attributes of the environment where they act (such as air temperature and air humidity) and other constants determined based on large scale experiments (such as clothing insulation and metabolic rate). This approach was developed by Fanger in the 1970s [3] and later it was refined in the ASHREA-55 standards. These models sought to ensure that a building equipped with HVAC systems is able to keep at least 80% of its occupants comfortable. However, a study of 215 office buildings in US, Canada, and Finland [4] showed that only 11% of the studied buildings had at least 80% of the occupants comfortable. Improper calculation of the setpoint temperature typically resulted in energy waste. Similar results were found by other studies [5–7].

Also, it was shown that attributes which were considered constant by the traditional model can change over time and can affect individual thermal comfort (such as clothing insulation, metabolic rate or age). For this reason, recent work in the literature has focused on developing HVAC control systems that add the occupants of the space into the control loop. This has been done in three ways: using occupants' feedback to adjust the set point temperature, using personal comfort systems for individualized comfort, or modeling individual thermal comfort. Setpoint adjustments based on user feedback were investigated in Refs. [8–10] by allowing the user to control the temperature through a local thermostat or by offering them an online system to provide feedback in real time. Advantages and possible issues with this

* Corresponding author.
E-mail address: cosmac@gwu.edu (A.C. Cosma).

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approach were analyzed in Ref. [11]. Their results showed that there was a significant gap between users expectations from the local temperature controller and the system designers perspective on the users needs.

The second approach for individual thermal comfort employed personal comfort systems (PCS), designed to keep occupants comfortable within their personal space. This approach proposed an energy efficient system by moving the focus from keeping the space within a set point temperature, to keeping smaller space enclosures within the set point temperatures. A few ideas were based on retrofitting office furniture, such as chairs [12] or desks [13], to integrate cooling and heating elements. Others focused on directing the air towards the occupant's location [14].

However, these first two approaches have a few limitations: they depend on user feedback, the user is required to physically interact with the system to achieve their desired results (such as turning a switch), and the user feedback is connected to a precise location, which is inapplicable if the user moves within the building (for example, to a conference room). For these reasons, a third approach was explored, which uses a mathematical modeling of thermal comfort based on physiological information extracted directly from individual occupants of the building. An in depth literature reviewed on thermal comfort modeling presented by Rupp et al. [15] showed significant growth of papers in this area. A large number of these studies (such as [16] and [17]) have focused on using existing datasets and machine learning algorithms to propose a better thermal comfort model than Fanger's PMV model using the same data as input. Some researchers, such as Liu at al. [18], focused on modeling thermal comfort using heart rate variability. Their results indicated that sympathetic activity was highly correlated with thermal discomfort, and the ratio between low and high frequency (LF/HF) components of heart rate variability (HRV) may be used as an indicator of thermal comfort. Other researchers have focused on extracting skin temperature, using sensors attached to the subject's body, to model thermal comfort based on human body thermoregulation [7,19–21]. Moreover, Chaudhuri et al. [22] showed that using normalized hand skin temperature based on inter-individual differences (such as clothing insulation and body surface area), the thermal sensation can be more accurately predicted. Similar results were found by Choi et al. in Ref. [23], which showed that body mass index (BMI) affects the temperature dynamics and that wrist temperature was the most significant body segment for assessing thermal sensation. Finally, Ghahramani et al. [24] collected skin temperature using eyeglasses outfitted with point IR sensors to monitor individual's thermoregulation. All these works showed that thermal comfort or sensation was correlated with thermoregulation, and that skin temperature can be used to model thermal comfort. Multiple body parts were identified as target points for thermal comfort modeling, but a few of them were highly sensitive to thermal comfort, such as wrist, head and chest.

A few more recent works focused on using thermographic cameras as a means to model thermal comfort. These cameras have the advantage of not requiring physical contact with the subjects while measuring their skin temperature. Preliminary studies focused on manual measurements of face temperature using hand-held thermographic cameras. Burzo et al. [25] used average facial temperature and other physiological signals to predict subject's level of discomfort without any explicit input from the user. Pavlin et al. [26] evaluated multiple forehead key-points as a measure of thermal comfort. Finally, Ranjan et al. [27] included head and hand temperatures manually extracted from a thermographic camera to model the thermal needs of the space occupants. All these works showed that average face temperature computed using thermographic cameras was highly correlated to thermal comfort, and that it can be used to predict the thermal needs of the building occupants.

Based on the results of these preliminary studies and the recent development of low-cost consumer grade thermographic cameras, we believe that these sensors are a promising technology to help solve the thermal modeling problem in an non-invasive way. While the above studies are based on hand-held cameras with explicit manual pointing for optimal measurement, we study the potential of a wall-mounted camera in a real office setting where the subject moves around and body parts are obscured or come in and out of the field of view, and where identification of thermal comfort is performed in real-time. The proposed sensing platform combines an inexpensive thermographic camera with a color-distance sensor to automatically localize measurements. Furthermore, we examine whether clothing temperature and identification of temperature differences amongst body parts can lead to more accurate assessment of thermal comfort. Finally, a comprehensive study with 30 healthy subjects was conducted to examine whether thermal comfort has a different signature from warm and cold discomfort in transient conditions.

2. Method

To test our proposed system capabilities to model thermal comfort levels, we designed an experiment based on an office setup with transient conditions, where we varied the office temperature and queried the thermal comfort of the occupants. Our proposed sensing platform was used to collect the thermal profiles of the following body parts: hand, elbow, shoulder, chest and head, including left or right. These body parts were identified as highly relevant for thermal comfort modeling by Refs. [21–23]. A feedback form was used to collect thermal comfort information from subjects. We describe in detail the proposed experiment in Section 2.1.

Our proposed non-invasive technology to automatically model thermal comfort combines three sensors, a thermographic camera, a depth sensor and a color camera, to create an augmented representation of the world, which we called RGB-DT (RedGreenBlue-DepthTemperature). This new world representation was used by our algorithms to detect and track humans within the environment, and to identify different human body parts for which the thermal profile was computed. This system is described in detail in Section 2.2.

Finally, all data collected by the sensing platform and subjects' feedback forms were used to analyze the interaction between genders, Thermal Comfort Vote (TCV) levels and body parts temperatures. The purpose of this analysis was two fold: verify if there is a difference in skin and clothing temperature response between males and females at different TCV levels, and validate the use of skin and clothing temperature as a mean of thermal comfort modeling. Complete data analysis can be found in Section 3.

2.1. Experimental design

2.1.1. Subjects

30 healthy volunteers participated in this study (15 females and 15 males), primarily undergraduate and graduate students at The George Washington University. Their age ranged between 20 and 42 years old. Every subject was asked to wear a similar outfit (such as pants, t-shirt and regular shoes) and was instructed on how to self-report their clothing insulation using the garment insulation table from Ref. [28]. Data from the 30 subjects showed that the average clothing insulation was 0.44 clo with SD = 0.07 clo. After we considered the added insulation when sitting on a chair (+0.1 clo for standard office chair), the final average clothing insulation was 0.54 clo. Metabolic rate was constant during the experiment, around 1–1.1 met, equivalent to sedentary office activity. All demographic measurements were recorded in a questionnaire at the beginning of the experiment and are presented in Table 1.

2.1.2. Office setup

The experiment took place in an office room at The George Washington University. The room was located in the middle of the School of Engineering and Applied Science building, and it had no