EXPLORING FUSING WEARABLES AND MOBILE TECHNOLOGIES TO OPTIMIZE ENERGY DEMAND AND OCCUPANT COMFORT

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Abstract: This research investigates a system capable of measuring and simulating occupant thermal comfort using mobile and wearable devices to adaptively control indoor environmental conditions to minimize energy and maximize comfort using smart-building technologies. Such research suggests a ground-breaking technical solution that provides new inputs for energy management and information systems using novel occupant-centered building sensor hardware-software methods and a set of custom metrics to evaluate thermal comfort of building occupants by fusing traditional human vital and physiological data streams. Recent technologies of wearable devices such as wristband devices are now able to capture a number of important and relevant parameters. To date, the team has successfully used ambient air temperature, relative humidity, skin temperature, perspiration rate, and heart rate, to explore new algorithms capable of assessing, in real-time, individual thermal comfort in buildings. The outcome is transformative as the potential of the proposed cost effective and unobtrusive system is to generate calibrated and adaptive assessment of individual thermal comfort based on actual occupant and spatial data. Broader impacts seek to collect and leverage big data regarding a range of individual behaviors and physiological signals within buildings.

1   INTRODUCTION

Commercial and residential buildings frequently fail to achieve optimum balance between occupant comfort and efficient operation (Mitterer et al. 2012). Furthermore, existing technologies and models of thermal comfort are cumbersome. Integrating human-in-the-loop and wearable technologies can address such challenges, while offering huge economic potential and environmental benefit. Specifically, studies have shown that efficient operation of commercial buildings can lead to 10% to 15% savings in annual energy cost (Nationalgrid 2002; TRC 2014). Additional studies estimate health and productivity benefits provide less than two years payback for investments related to improving indoor environmental quality (Wargocki and Seppanen 2006).

Existing representations of thermal comfort, however, are outdated and inadequate. Algorithms used to measure thermal comfort using the Predicted Mean Vote (PMV) index were developed in the 1970s, yet are still adopted by the American Society of Heating Refrigeration Air Conditioning Engineers (ASHRAE) in Standard 55. Existing equipment used to measure thermal comfort is frequently bulky, expensive, and stationary. Accordingly, such assessment is impractical, and incapable of continuously monitoring comfort level and location of building occupants (ANSI/ASHRAE 2010; Fanger 1970).

A number of studies have been conducted to investigate the use of wearable devices, wireless sensors, and mobile applications for identifying thermal comfort of building occupants and their location over time. A recent study developed a battery-powered indoor environment sensor to recognize activity type and location based on environmental measurements. The developed device is designed to provide easily deployable

sensing infrastructure that can operate for years in a smart buildings or be wearable and portable. The developed device showed that fusion of environmental sensing along with acceleration can achieve classification accuracy up to 99.13% (Jin et al. 2014). Another study investigated the use of wireless systems to compute thermal comfort in indoor environments; however, it should be noted that the wireless sensors did not measure mean radiant temperature and air velocity (Aswathanarayanajois 2013). Another system was developed to improve thermal comfort for Ambient Assisted Living (AAL) by continuously monitoring indoor environmental parameters that lead to an accuracy of ±0.1 of PMV for multiple positions or occupants in a room. The developed system can be integrated with building management systems to adjust the indoor environment to required comfort level. The system uses infrared sensors to automatically scan the surfaces inside a room and identify their temperature. (Gian Marco Revel et al. 2014). Another on-going research at NREL seeks to continuously record a user's thermal comfort to support the development of an Adaptive Wearable Thermal Comfort System (Chin 2015). Additionally, a mobile application called "Comfy" is commercially available and allows occupants to manually adjust temperatures in their surrounding by connecting cell phones to building systems (Comfy 2015). Finally, several systems also exist that rely on prediction models using fuzzy rule-based algorithms that extract underlying patterns in collected data (Klein et al. 2011; Yang and Wang 2013; Yang et al. 2012).

Despite the significant contribution of these existing systems and models, they typically have limited capability for dynamically managing building operation and comfort. Existing models fail to identify thermal sensation of building occupants based on physiological and environmental factors that can be collected using wearables. Furthermore, no reliable optimization algorithm exists using human-in-the loop sensor and control systems that can identify indoor environmental conditions to maximize comfort while minimizing energy demand.

In stark contrast, our technique collects and utilizes four kinds of physiological signals including skin temperature, heart rate, skin conductivity, and activity level, to estimate individual's comfort level. With a convergence of four suitable sensors, bio-metrics can be measured unobtrusively, continuously, and accurately. Human skin temperature, for example, is easily measured using a body temperature sensor embedded on a wearable. Powered by red and infrared light emitters, an optical blood flow sensor could measure the heart rate. In order to sense the level of moisture of human skin, a galvanic skin response sensor is utilized. Various types of human activities could be tracked by fusing 3-D accelerometer, gyroscope, and magnetometer readings together, which in turn can be used to estimate the calories consumed. By merely combining of these sensors, one has a reasonably accurate sense of how comfortable a person is.

2   THERMAL COMFORT SYSTEM

To leverage this opportunity, the authors are developing a new system, which consists of three primary functional components: sensing, controlling, and reporting. Sensing System: Uses wearable and mobile devices to continuously monitor physiological and vital signals of the occupants to determine thermal comfort levels taking into account not only the environmental conditions (temperature, air pressure, brightness and light level etc.), but also the individualized information of the occupants (activity level, heart rate, respiration and perspiration rates, etc.). Bluetooth Low Energy (BLE) beaconing devices are used to generate room-level location information. Autonomous Real-time Controller: Uses a centralized server to adapt local indoor environments. Adjustment are actuated through smart vents, smart thermostats, and smart blinds readily installed in targeted rooms. It is important to note that these smart building technologies are pervasive in modern built homes and readily available for retrofitting as needed. Thermal Comfort Reporter: Allows building owners and occupants to visualize the thermal comfort level of the buildings or individual rooms over time. Such reports provide visualizations through graphs, heat maps, or other representation forms, displayed on mobile devices, online web portals, or local repositories.

Figure 1 is a diagram of the new system and its components to assess, optimize and report thermal comfort. The research team was working under a provisional patent related to the development of this system.
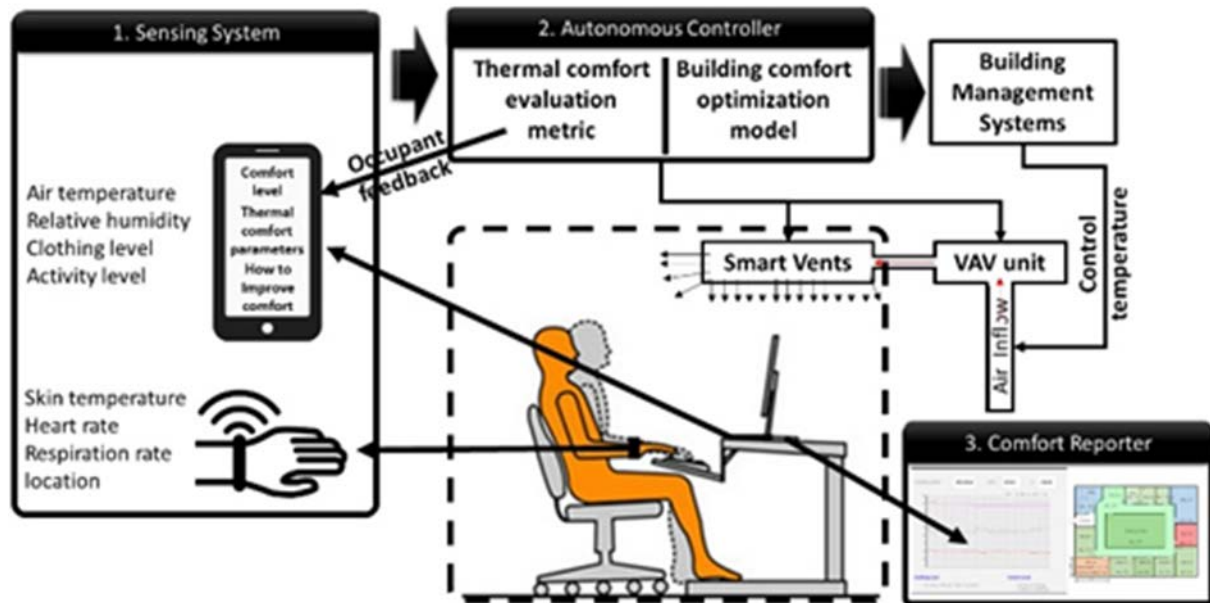
Figure 1: Layout of building operation optimization system

3 PILOT TESTING

The authors have conducted a pilot study to investigate the feasibility of using wearable devices to measure thermal comfort.

3.1 Design of Experiment

The pilot study focused on (1) testing a custom mobile application in collecting data of indoor environmental conditions and physiological signals, (2) identifying the accuracy of the collected data using wearable devices, and (3) studying the feasibility of estimating or calculating PMV index based on the collected data of indoor environmental conditions and physiological signals.

The pilot study was conducted in a conditioned laboratory at University of Colorado Denver within varying indoor environmental conditions. Equipment used to complete the study included four cellphones using a custom application, four Basis wristband devices (BASIS), Delta OHM HD32.3 thermal comfort equipment and four iBeacons. The custom application served to automatically collect and aggregate data from cell phone and wearable sensors on thirty second intervals. In addition, users were prompted by the application to manually select an activity and assign a comfort level using 7-point scale of the PMV index every fifteen minutes via cell phones. The experiment took place in a laboratory space, with three additional iBeacons placed in locations around the floor of the building. An electric heater was placed in the laboratory to change the temperature during the experiment.

3.2 Data Collection

Cell phone sensors were used to collect air temperature and relative humidity data. Wearable sensors were used to collect skin temperature, heart rate, and skin conductivity along with air temperature and relative humidity data. Wearables were worn on the wrists of participants with no clothing occluding the wearable. The recordings of the indoor environmental conditions and physiological signals were recoded with time

stamps. Finally, thermal comfort equipment consisting of the data logger and probes were used, in some cases redundantly, to log mean radiant temperature, air velocity, air temperature and relative humidity in the space. The thermal comfort equipment had been recently calibrated by the manufacturer, and, its data, therefore, was considered to be "ground truth" for the research.

3.3   Analysis and Results

The data collected for each participant was organized and analyzed using the following techniques: data smoothing and alignment; and machine learning. Data was smoothed based on five-minute intervals and aligned with the thermal comfort equipment based on a one-minute basis. Artificial Neural Networks ANNs were used to estimate the PMV output relative to a number of inputs.

The collected data showed variations across devices when measuring air temperature and relative humidity. The authors performed a separate analysis comparing cell phone sensors and thermal comfort equipment. For this test, the four test cell phones were placed side by side on the table along with the air temperature and relative humidity instrument probe for an hour, while the indoor environmental conditions varied. Results of this analysis revealed discrepancies in measured air temperature and relative humidity across all devices even after data smoothing. Accordingly, the authors concluded that sensors both cell phone and wearable devices lacked a degree of accuracy and will require additional testing and calibration in the future.

For the pilot study, collected data was analyzed as inputs and using ANN to calculate PMV index. Analyses of several sets of input parameters was performed using NeuroSolutions Infinity to predict PMV values (NeuroSolutions 2015). The results of the best model indicated that physiological and environmental factors that can be readily measured using wearables have 99.9% correlation to traditional occupant comfort estimates of PMV. The input parameters of the best model were identified as air temperature, square root of the summation of perspiration and air temperature, summation of perspiration and relative humidity, skin temperature, and heart rate with contribution to PMV index of 28.1%, 27.9%, 19.2%, 12.8%, and 12.1%, respectively.

In general, however, findings of the pilot data identified a number of challenges for the system including, occlusion by clothing, skin connectivity, and accurate identification of location for building occupants. To address such challenges additional customization of wearables devices is being performed to overcome the inaccuracy and non-optimized design of commercially off-the-shelf wearables. For example, assessing thermal comfort of building occupants does not require frequent measurements compared to other applications (every 5 minutes versus every 5 or 15 seconds). Sensing optimization includes employing an adaptive sampling frequency technique. If the person is relatively stationary, the sensors will measure their biological and vital signals less frequently compared to when the person physically active. Another optimization technique being explored is having many more sensors of the same type on the wearable to make the measurement more accurate, yet perform measuring very infrequently. In short, one could improve the sensing accuracy without increasing power consumption. An example is having multiple electrodes to measure temperature would be better than having a single one. With more electrodes distributed on the contact area of the wearables, it is more likely that at least one of the electrodes will make contact with the skin (i.e. leading to a more accurate measurement compared to having a single one). To make up for the extra energy being used by multiple electrodes, the sampling rates could be reduced from 100 Hz down to 0.1 Hz, which is still considered sufficient for most purposes of body temperature measurement. Finally, and in parallel, the use of optimized iBeacons technologies or Project Tango, a Google platform for giving phones and tablets a sense of space, is being explored for more granular and interactive location mapping.

4   RESEARCH CONTRIBUTION

By fusing traditional environmental sensing data with newly available wearable sensing information our team is creating (1) new models for measuring human thermal sensation including physiological signals and factors not considered in existing models; (2) new metrics to provide accurate and meaningful feedback to building owners and operators in order to identify the optimal trade-off between building comfort and

building operation, (3) thermal comfort report cards that can rate spaces and buildings according to occupant comfort, and (4) commercializable system that adapts indoor ambient environments to maximize thermal satisfaction using smart-building technologies.

4.1 New Model Development and Validation

The project team is currently investigating the correlation of physiological signals along with other factors such as gender, age, movement, and core temperature to thermal comfort of building occupants. The outcome will be a list of definitive list of physiological parameters that are useful for creating a proxy of the traditional PMV model using mainly wearable devices and cell phones for data collection.

Once this new model of thermal comfort is fully developed, the project team plans to conduct additional and comprehensive experiments to correlate the list of parameters identified to predicted thermal comfort of building occupants. Experiments will include a range of dynamic indoor environmental conditions including air temperature, relative humidity, air speed, and mean radiant temperature, clothing levels, and activity levels. Laboratories at the University of Colorado Denver as well as the Thermal Test Facility (TTF) National Renewable Laboratory (NREL) are likely test sites.

4.2 New Metric

Currently, ASHRAE Standard 55 evaluates a space in a binary fashion, as either meeting thermal comfort requirements (falling within the prescribed region on the psychometric chart) or not [13]. Normalized comparison, however, requires a scalar metric. Therefore, our team has identified comfort level boundaries in the temperature-relative humidity chart based on the six parameters considered in ASHRAE Standard 55 and has divided into 11 zones of different comfort levels, and represented by a score ranging from 0.0 (least comfortable) to 10.0 (most comfortable) (Abdallah et al. 2015). Using this scalar metric, it is now possible to compare and score thermal comfort between individuals and across spaces and buildings.

4.3 Reporting

To date, the team has developed a thermal comfort report card, and is developing a website and interface to evaluate overall and discrete thermal comfort for building occupants based on room-by-room comfort levels through time and building thermal performance annual average. The cloud-based database serves as a repository and viewer that allows users to evaluate the thermal comfort of selected building occupants using previously identified physiological signals and additional physical parameters (Figure 2).
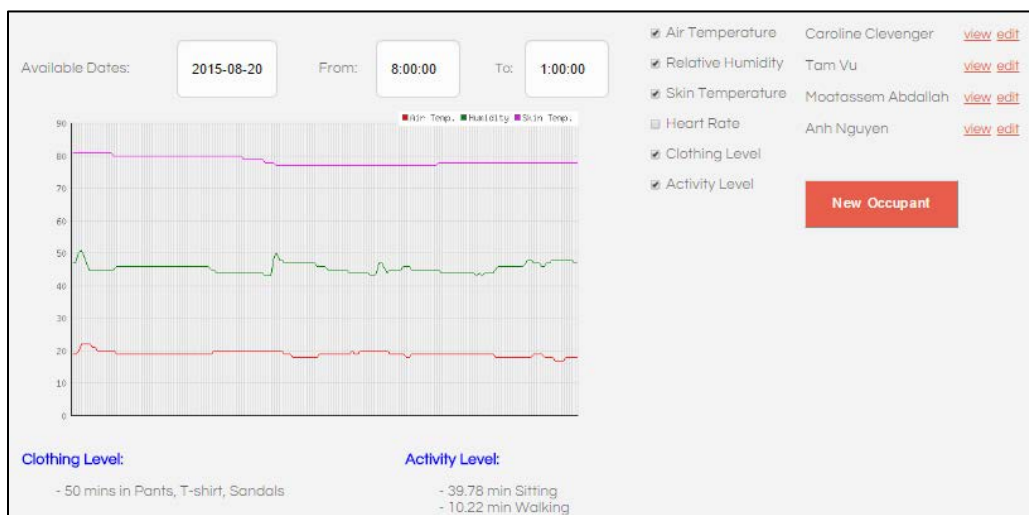

Figure 2: Thermal Comfort Reporting Webpage

A room comfort score is calculated based on the average comfort score of all occupants in a room. Finally, an overall thermal comfort score of a building is then calculated based on the room comfort score, room surface areas, and building surface area. Reported feedback and scores provided building occupants will be used to further validate the new thermal comfort metric, provide feedback on the actual performance of ASHRAE Standard 55 in real buildings, and provide a new, normalized method for comparing performance across buildings.

4.4   Leveraging Smart-Building Technologies

Our proposed system is built around three key hardware components including personal wearable devices, localization beaconing devices, and a centralized controlling server capable of communicating with existing smart-building technologies. The central server continuously receives individual sensing data streams in real time. An agent implements the outcome of the optimization model and wirelessly controls off-the-shelf smart-building technologies such as thermostats, automated shades, VAV units, and smart vents.

Several approaches are being investigated including making use of both Bluetooth low energy (BLE) and WiFi in combination with near field communication (NFC). Specifically, leveraging iBeacon protocol developed by Apple, the first communication link can be BLE, established between the localization beaconing devices and the wearable. For the connection between sensors on the human body, active NFC (or other intra-body communication technique such as ultra-sonic based communication) can be used to provide a low cost and short range data transmission link. WiFi is used for connections between the wearable devices and the server for streaming both the occupants' vital data and their location. The same communication technology can be used between the server and the smart vent system, and between the server and the thermostats of the building for controlling them in real time.

5   BROADER IMPACTS

Nearly everyone has experienced thermal discomfort inside a building. Such discomfort and the associated lack of productivity is non-trivial particularly when Americans spend more than 90% of their time indoors. Our new research direction capitalizes on the fact that occupant thermal comfort can lead to higher occupant productivity and optimum energy usage in buildings. The objective is to use wearable and mobile devices to measure, monitor, and optimize thermal comfort of building occupants. Additional and potentially more far-reaching benefits include big data collection regarding individual behavior and physiological signals within and across buildings.

5.1   Acknowledgements

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