

Design of Low-cost Sensor-based Solution to Support Thermal Comfort

Carlos Zepeda-Gil¹[0000-0002-2828-2383], Matias Garcia-Constantino²[0000-0002-3420-0532] and Alexandros Konios³[0000-0001-5281-1911]

¹ Universidad de Monterrey (UEM), 66238, San Pedro Garza García, Mexico,

² School of Computing, Ulster University, Belfast Campus, BT15 1AP, United Kingdom,

³ Department of Computer Science, Nottingham Trent University, Nottingham, UK
carlos.zepeda@udem.edu, m.garcia-constantino@ulster.ac.uk,
alexandros.konios@ntu.ac.uk

Abstract. The effects of global warming caused by human activities have impacted people's daily lives around the world with more frequency in the last 20 years. It is estimated that by 2050 the global temperature will increase by 3°C with respect to 2020. These increases in temperature have been noticeable in recent years with heatwaves, extreme temperatures, and draughts, particularly affecting areas with already high temperatures. This paper presents an initial design of a low-cost sensor-based solution to support thermal comfort in homes (rooms or areas in the living space) in the northeast of Mexico, where temperatures already reached 45°C in 2024. The solution proposed is comprised by three types of ambient sensors (movement, temperature and humidity), and a smart ring wearable sensor. The sensors will first collect data to build a profile of the environment and the users, and then to detect conditions that are not safe for the users, such as extreme high and low temperatures based on their personalised profile. This data will be complemented with thermal comfort surveys and self-perceived health surveys. Relevant information will be displayed to users in a user-friendly dashboard.

Keywords: Thermal Comfort, Sensor-based Solution, Smart Home, Temperature

1 Introduction

Climate change poses the most significant threat to humanity [1]. During global summits in the year 2000, world leaders established a target of limiting global warming to 2°C above pre-industrial levels by 2020 [2]. Unfortunately, this ambitious goal was not achieved, prompting a revised target of limiting global temperature increase to 3°C by 2050. Meeting this goal would have less severe consequences compared to a higher temperature increase exceeding 5°C, as predicted by models developed by NASA and other institutions [3]. Such an increase would result in more frequent and intense heatwaves, as well as longer and more frequent cold spells during the cold season.

The World Health Organization (WHO) highlights the health risks associated with prolonged exposure to both low and high temperatures [4]. Additionally, studies indicate that, on average, individuals spend approximately 90% of their day indoors [5]. Among specific population segments, such as homemakers, this indoor time is predominantly within residential spaces, including dormitories and living areas [6]. Consequently, ensuring thermal comfort within indoor environments becomes crucial. Vulnerable groups, including individuals with chronic illnesses, the elderly, children, and those who remain indoors throughout the day, face heightened risks in such conditions. Hence it is necessary to ensure that both residential and non-residential dwellings are currently providing adequate environmental conditions such as temperature and relative humidity that had proven to be relevant in the thermal sensation of the occupant of a building.

This study presents a design methodology and a user-friendly dashboard for real-time monitoring of environmental conditions. The primary focus is to ensure that residential and non-residential buildings maintain healthy environments (temperature, relative humidity, air quality). However, the challenge of unhealthy homes often arises in situations of energy poverty, where occupants intentionally endure thermally uncomfortable environments to manage energy costs. Surprisingly, no studies have investigated real-time actions taken by populations concerning thermal comfort. Existing research suggests that awareness of environmental conditions [7], coupled with real-time energy monitoring [8], can enhance occupants' thermal adaptability (e.g., wearing warmer clothing, consuming hot beverages) without significantly increasing energy consumption. Thus, it is crucial to develop a solution that employs low-cost sensors to monitor environmental conditions, providing real-time feedback to occupants while promoting an intelligent and accessible environment for people.

2 Literature Review

2.1 Thermal Comfort

The definition of thermal comfort has been widely accepted as “the condition where the mind expresses satisfaction within the thermal environment” [9]. The two most accepted theories are the Steady-State (Predicted Mean Vote, PMV) theory developed by Fanger [10], and the Adaptive Model developed by Humphreys and Nicol [11]. Both theories are based in asking the studied population to vote their thermal state in a 7-point scale that ranges from cold (-3) to neutral (0), and to hot (+3). The PMV theory was developed in climate chambers and was specifically designed for mechanically ventilated buildings and is included in the widely accepted standard ISO 7730 [12]. It aims to predict the average thermal vote of a population within a space, i.e., if within a room 10 people vote 0 (neutral), and 3 people vote +1, then the mean vote would be +0.23. The formula included in the ISO 7730 standard aims to predict this mean vote. On the other hand, the Adaptive model included in the ASHRAE 55 [9] (American Society of Heating, Refrigerating and Air Conditioning Engineers) states that thermal comfort is not based on a fixed temperature, but rather that a human can withstand a

range of temperatures given their adaptation possibilities. These are physiological (i.e., body's thermal homeostasis), behavioural (drinking a hot beverage when too cold, etc.) and psychological (ability to adjust room's temperature). This method was designed for naturally ventilated buildings. In fact, there is evidence that people in naturally ventilated buildings feel thermally comfortable at a wider range of temperatures.

The formula to predict the Mean Vote of a population includes 6 variables, among which 4 are environmental (external temperature, internal (operative) temperature, relative humidity and wind speed) and 2 personal (metabolic activity and types and layers of clothing). The formula of PMV provides a result simulating the thermal vote of a room, where if it ranges between $-0.2 < \text{PMV} < +0.2$, the space would be ranked as "category 1". This is for spaces occupied by people with chronic illnesses, very young children, or the elderly. Category 2 lies in the range between $-0.5 < \text{PMV} < 0.5$ and Category 3 buildings $-0.7 < \text{PMV} < +0.7$, where Category 2 is for new or newly refurbished buildings, and Category 3 for existing.

2.2 Healthy temperature ranges

Overheating. The standard CIBSE TM59 [13] provides the criteria for defining overheating in homes, particularly those naturally ventilated. It measures overheating based on the difference between the internal (operative) temperature, and the maximum temperature, allowed by the Adaptive method. The first criterion (1A) for overheating included in the TM59 establishes the Hours of Exceedance, that sets the duration of overheating in living rooms, kitchens and 24h for bedrooms. To meet this criterion, the Hours of Exceedance should be less than 3% of total occupancy hours from May to September. Criterion 1B states that in bedrooms, between 22:00h and 7:00h, the Hours of Exceedance must not be more than 1% of the total hours of the whole year. The Criterion 2, Daily Weighted Exceedance, addresses how severe overheating is on any given day. In this Criterion, the Daily Weighted Exceedance should be ≤ 6 per day. The Criterion 3 establishes an upper limit on the daily internal temperature. If this limit is surpassed, then the overheating level becomes unacceptable.

Underheating. To our best knowledge, there isn't a standardized measurement for the degree of cold in any type of building. Hence, we will employ an underheating model [14] to address this issue. This model allows us to determine whether a building provides sufficient warmth during the cold season, and the severity of underheating. This model was set using the CIBSE TM59 standard as a benchmark, but instead of using the upper threshold of the adaptive chart [15], it considers 18°C as a lower threshold, given that the WHO mentions that long exposures below this temperature can be detrimental to human health. This model uses a ΔT_{min} , that is the difference between the 18°C and the operative temperature. Criterion 1 uses the Hours of Exceedance of the lower threshold. In this criterion, the total number of hours where $\Delta T_{min} > 0$ should be less than 3% of the total hours of the entire year. Criterion 2 assesses the severity of underheating, i.e., the severity of damage increases as the operating temperature decreases.

3 Methodology

3.1 Site

The selected site is within the northwest of Mexico, within the urban area of the city of Monterrey, Mexico (Lat = 25.67°, Lon = -100.31°). The city is surrounded by the mountain chain “Sierra Madre Oriental”, however the city was developed over the valley below the mountains with an altitude of 512m. The urban area has a ratio of approximately 5.3M people, making it the second biggest urban area in Mexico, with a density of 700p/km². The city has two Köppen climate classifications, one being BSh (Hot semi-arid), and towards the south of the city it has Cfa (Humid subtropical). We will deploy our study only on the area under BSh climate, as it predominates the most over the northwest of Mexico, and even the south of Texas in cities like San Antonio. The coldest month is January where the minimum average (from 1991-2020) was of 9.6°C, and the maximum average is august with 29.4°C. However, it reached up to 45°C during May 2024. It rains on average 590mm per year, mainly from June to October. It has 2,240 sunshine hours per year, and an average relative humidity of 55%.

3.2 Participants

As this study is yet to be undertaken, this subsection presents the proposed sample selection, to assure both, that recruitment methods are correct, the sample is not biased, and that homes and participants are comparable to each other. We aim for participants living in homes without insulation nor double glazing. It is also important that the rooms where the sensors will be placed are not located north, as these will not be the hottest spaces in the house. Due to ethics, participants should be older than 18 years old), however, this study is not targeted to a particular social sector, gender, or age group, hence these variables stay open.

3.3 Surveys

The two step adaptive cluster recruitment method [16] requires a pilot study to be deployed prior to the main one. Hence, this will be launched during the month of August, given that it is the hottest month. It is planned that we will undertake one visit per week, where the information to be collected is described as follows.

First visit. (i) dwelling information (orientation, window ratios, aspect of the house, and confirm that there is no insulation nor double glazing, and number of rooms), and (ii) personal information (age, occupation, income, weight and height, gender, and highest level of studies).

Consequent visits. (i) thermal comfort (surveys using the 7-point thermal comfort from the ASRHAE 55 standard, with the PPD and PMV variables being monitored), (ii) health (questions regarding self-reported physical (including heart pressure and

oxygenation) and mental health will be asked, similar to a previous study [14]), and (iii) fuel poverty (questions related to challenges when paying energy bills during the hot season, as well as if they stopped using air conditioning to keep energy bills low).

3.4 System Architecture

For the pilot study, we aim to test the functioning of two micro-computers: (i) Raspberry Pi 3 Model B, and (ii) NVIDIA Jetson. In this case, we plan to deploy 10 Raspberry Pi and 2 NVIDIA Jetson micro computers during the pilot study stage. Later we will identify the functioning of both systems to decide the main microcomputer to undertake the main part of the study. In addition, the following sensors will be attached to the micro-computers, with the exception of the smart ring, that will be worn by the subjects: (i) Oiyagai infrared PIR HC-SR501 (movement), (ii) Advanced MLX90641 D55 thermal camera, 16x12 pixels (thermal), (iii) Hailege MLX90614 infrared temperature sensor (temperature), (iv) Temperature sensor DS18B20 (temperature), (v) Relative Humidity Sensor DHT22/AM2302 (relative humidity), and (vi) Ring Taisuko Model TSK-SZSR-000 (wearable smart ring).

3.5 Data Analysis

The thermal comfort prediction stage involves the following stages: (i) monitoring data and transferring to a microcomputer, (ii) to transfer the data to a cloud service, (iii) store and process data using our deep learning algorithm, and (iv) once the thermal comfort prediction has been issued, the IoE system will act accordingly, either modifying the internal temperature through local fans or air conditionings, or by alerting the user. Artificial Neural Networks (ANNs) will be used to construct our thermal comfort predictive model, in particular, a Multi-Layer Perceptron (MLP) framework. Supervised Deep Learning techniques will also be applied, where during learning, a training dataset will be provided to the neural network, with each input observation paired with a corresponding output value. This will allow the neural network to learn the output associated with each input. For instance, our dataset observations will be categorized into seven distinct PMV classes.

4 Conclusions

This study outlines the methodology for capturing real-time data that will be uploaded and analysed instantaneously, with the aim of providing live feedback to users and/or the Internet of Everything (IoE) system where it will be implemented. Additionally, this research investigates a new thermal comfort prediction model tailored for the northeastern region of Mexico, where temperatures can soar up to 45°C and cardiovascular diseases are the leading cause of death. Consequently, monitoring key health indicators and their relationship with extreme seasonal temperatures is crucial for this population.

5 References

1. Kjellstrom, T. and A.J. McMichael, *Climate change threats to population health and well-being: the imperative of protective solutions that will last*. Global health action, 2013. **6**(1): p. 20816.
2. UN-HABITAT, *Global Report on Human Settlements*. Global Report on Human Settlements, 2011.
3. NASA. *Climate Chnage*. From the unique vantage point in space, NASA collects critical long-term observations of our changing planet. 2024 [cited 2024 24/07/2024]; Available from: <https://science.nasa.gov/climate-change/>.
4. WHO, *WHO housing and health guidelines*. 2018, World Health Organization: Switzerland.
5. Höppe, P. and I. Martinac, *Indoor climate and air quality*. International journal of biometeorology, 1998. **42**(1): p. 1-7.
6. Brasche, S. and W. Bischof, *Daily time spent indoors in German homes – Baseline data for the assessment of indoor exposure of German occupants*. International Journal of Hygiene and Environmental Health, 2005. **208**(4): p. 247-253.
7. Zepeda-Gil, C. and S. Natarajan, *Thermal comfort in naturally ventilated dwellings in the central Mexican plateau*. Building and Environment, 2022. **211**: p. 108713.
8. Vellei, M., et al., *The effect of real-time context-aware feedback on occupants' heating behaviour and thermal adaptation*. Energy and Buildings, 2016. **123**: p. 179-191.
9. ASHRAE, *ANSI/ASHRAE Standard 55-2013, Thermal environmental conditions for human occupancy*. 2013: Atlanta, Ga.
10. Fanger, P.O., *Thermal comfort. Analysis and applications in environmental engineering*. Thermal comfort. Analysis and applications in environmental engineering., 1970.
11. Nicol, J.F. and M.A. Humphreys, *Thermal comfort as part of a self-regulating system*. Building Research and Practice, 1973. **1**(3): p. 174-179.
12. ISO, *7730: 2005. Ergonomics of the thermal environment—Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria*, 2005.
13. Cibse, T., *Design methodology for the assessment of overheating risk in homes*. The Chartered Institution of Building Services Engineers: London, UK, 2017.
14. Zepeda-Gil, C. and A.J. Montiel-Castro, *Cold Housing in Central Mexico: Environmental Dissatisfaction and Underheating Lowers Self-Perceived Health in Central Mexico*. Buildings, 2023. **13**(3): p. 814.
15. Nicol, F., M. Humphreys, and S. Roaf, *Adaptive thermal comfort: principles and practice*. 2012: Routledge.
16. Thompson, S.K., *Adaptive cluster sampling*. Journal of the American Statistical Association, 1990. **85**(412): p. 1050-1059.