Biography and Outline of Research Thesis

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【Biography】

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【Title of Research Thesis】

Affect-Aware Intelligent Thermal Comfort Environments

【Outline of Research Thesis】

I. Background

Thermal comfort provision is energy-intensive. Buildings consume 40% of the global energy, spending a large portion of it solely on thermal comfort provision [11]. However, despite the dedicated energy resources, thermal comfort provision mechanisms (e.g., air conditioning units) are ineffective, and the majority of building occupants complain about the lack of adequate thermal comfort [5, 6].

By definition, thermal comfort is "that the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation" [2]. Therefore, thermal comfort is a psychological sensation that varies from one person to another. Paradoxically, however, most thermal comfort provision technologies (e.g., air conditioning units) provide neutral thermal conditions to all occupants of the buildings. Unfortunately, this strategy is inefficient and has many well-known flaws highlighted in, e.g., [4]: First, a one-size-fits-all strategy cannot work well because of individual differences (e.g., age, gender, and physiological makeup) that influence how each person perceives thermal comfort [10]. Second, in reality, people prefer non-neutral conditions [3]. Third, achieving thermal neutrality is costly and necessitates immoderate energy consumption [11]. Forth, only a few parts of the body (e.g., head, wrists, and feet) are mostly responsible for thermal comfort. For example, in uniform environmental conditions, when it is cold, a person's feet and hands feel colder than other parts of the body.

On the contrary, the cold environment does not affect the thermal sensation on the head, which usually feels warmer than the rest of the body and requires a relatively lower temperature to achieve a satisfactory thermal comfort [1]. However, air conditioning units do not exclusively direct the heat to these crucial parts of the body. Instead, they inefficiently cool or warm an entire room and regardless of the number of people available in the room. Lastly, current international thermal comfort standards are unambitious (they expect a mere 80% satisfaction rate[2])—a scant performance that is rarely met in practice [6].

Recent awareness campaigns for a sustainable economy have led policymakers to enact energy reduction regulations. However, technological limitations seem to thwart this effort. For example, a mandatory energy-saving policy, which was introduced by the Japanese government, resulted in an increased thermal dissatisfaction and a reduction in productivity [9]. Thus, delivering higher-quality thermal comfort at lower energy consumption is a conundrum that requires a paradigm shift in how thermal comfort is provided [8].

II. Research Problem and Hypotheses

Current thermal comfort mechanisms consume much energy, yet, they provide inadequate thermal comfort. This thesis proposes to resolve this conundrum by mitigating the gap between the quality of the provided thermal comfort and the required energy consumption in an office environment. The thesis proposes to provide thermal comfort based on the person's physiological changes due to his surrounding environment.

Indeed, humans maintain their body core temperature via a thermal regulation process that is mostly controlled by the brain's hypothalamus, which serves as the "thermostat" of the body. In a nutshell, the hypothalamus receives sensory inputs from thermo-receptors located in the skin, liver, and skeletal muscles and initiates appropriate processes to keep constant the body's core temperature. For instance, when it is hot, the hypothalamus activates heat-dissipating and body cooling mechanisms such as sweating and vasodilation. Conversely, when it is cold, the hypothalamus activates thermogenesis mechanism (e.g., shivering in skeletal muscle and heat generation in brown adipose tissues) and other mechanisms to reduce heat dissipation (e.g., cutaneous vasoconstriction and piloerection) [1].

Considering that thermal comfort is, by definition, a psychological sensation, and depends on the human thermoregulation, and given that thermoregulation activities induce detectable physiological changes, this thesis hypothesize that thermal comfort state could be more accurately estimated based on the variation in the person's heart rate variability (HRV). The detected thermal comfort state could be used to fully automate indoor air conditioning based on people's thermal comfort level. Unlike existing thermal comfort estimation models, this approach would provide personalized thermal comfort to reflect each individual's thermal comfort expectations. Further, by this approach, it could be possible to significantly reduce the required thermal comfort provision energy by letting the indoor temperature drift away from thermal neutrality and adjust it only if people are about to feel thermally uncomfortable. Also, unlike existing systems that cool or warm an entire room, including its walls and furniture, and regardless of the number of people present, the proposed approach could utilize a combination of centralized air conditioning and personalized thermal comfort provision systems in order to channel the thermal comfort to these parts of the body that are mostly responsible for the thermal discomfort. This may result in a higher quality of thermal comfort and would require less energy.

III. Research Methodology

Experiments were conducted in thermal chambers and recorded the subjects' electrocardiogram (ECG). The ECG signal is used to computed HRV, which serves as an input to machine learning models that predict the comfort state (cold, neutral, and hot) of each subject. Thermal comfort is provided by creating a microclimate comfort zone around a person whereby the person's thermal comfort is estimated from the change in his/her heartbeat patterns. After that, appropriate utility functions could be used to select the most suitable thermal provision methods to meet everyone's thermal comfort needs at the lowest energy.

IV. Outline of the Thesis

Chapter 1 serves as an outline of the thesis. It discusses why the research in the thesis was conducted, its main findings, its implication and discusses its limitations

Chapter 2 overviews the advances in thermal comfort provision in buildings. It examines the advantages and limitations of the predicted mean vote (PMV) model and why its successor—the adaptive thermal comfort model—also falls short in the age of global warming and summer heatwaves. Finally, the chapter examines the forefront research in thermal comfort and discusses the emerging concept of "human-in-the-loop thermal comfort" and explains its advantages.

Chapter 3 takes inspiration from experimental researches on human thermal regulation, human thermal physiology, human cardiology, and human neuroscience and investigates the possibility to monitor people's thermal comfort from the variation in their physiological signals. In particular, it investigates the influence of thermal comfort environments (cold, neutral, and hot) on human heart rate variability (HRV). It also examines the effect of low-power neck-coolers on people's thermal comfort perception and their physiological signals. Various experiments conducted on human subjects lead to two important conclusions. First, the change in the thermal environment distinctively alters people's HRV, and that heartbeats are more regular and less complex in comfortable environments and exhibit a more complex pattern in cold and hot environments. Second, in hot environments, neck cooling improves people's subjective perception of their thermal environments and leads to heartbeat patterns that are similar to what people would have had in a less warm environment.

Chapter 4 continues where Chapter 3 left off and investigates the possibility to predict thermal comfort from people's HRV. The results in this chapter strongly suggest that it is possible to design automated thermal controllers that predict people's comfort state based on their HRV. Two types of machine learning models were developed. The person-specific models were trained on the data of the same subject and evaluated using 10-folds cross-validation. It was found that person-specific models perform quite well (accuracy > 95%); however, their usage is limited only to one specific person. On the contrary, the versatile generic models that could be used to predict the thermal comfort of any person do not work well (50%<accuracy<60%). Indeed, thermal comfort is expressed differently from one person to another. Consequently, generic models cannot work well.

Chapter 5 introduces the architecture of a personalized thermal comfort delivery mechanism that is regulated by people's physiological responses to their surroundings. The proposed strategy makes it viable to create an adaptive and personalized micro-climate comfort zone around a person or a group of people in an intelligent environment. Each occupant's thermal comfort is estimated from a variation in his/her physiological signals. Henceforth, suitable constraint optimization algorithms can be used to decide the most appropriate thermal provision methods that meet everyone's thermal comfort needs at the lowest energy. Finally, the chapter presents a prototype of a system that estimates and delivers thermal comfort, in real-time, based on a person's HRV computed from a wrist photoplethysmogram (PPG) signal.

Chapter 6 examines the influence of stress on HRV, the theoretical interplay between stress and thermal comfort, and investigate the feasibility to distinguish HRV due to thermal distress from that due to work stress. It shows that, like thermal comfort, stress varies from one person to another; consequently, although personal specific models perform well in stress recognition, the generic models perform crudely. The results in this chapter also suggest that, although both thermal comfort and work stress affect HRV, in an office environment, unless a person is both stressed and thermally dis-comfortable, most ephemeral changes in HRV are due to either work stress or thermal discomfort.

Because thermal comfort varies from one person to another, a practical thermal comfort system based on the approach proposed in this thesis would only work if person-specific models are used. Unfortunately, this would be expensive and may not operate well as expected because thermal comfort is dynamic and changes depending on unforeseeable factors. **Chapter 7** proposes a practical and cost-effective calibration algorithm that derives an accurate and personalized affect (e.g., thermal comfort and stress) prediction machine learning model from physiological samples collected from a large population. The chapter also discusses the author's vision of how the proposed calibration algorithms could be used in an intelligent environment that delivers an efficient thermal comfort and improves the well-being of the occupants of the building.

Finally, **Chapter 8** provides a general conclusion of the thesis and discussed the practical implication and limitations of its findings.

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Publications

(only publications related to this research)

Outline (co-author)

- Journals	3	(2)
- International conf.	7	(3)
- Local symp.	1	(2)
- Awards	1	

Scientific Journals

[J1] K. Nkurikiyeyezu, A. Yokokubo, G. Lopez, "The Influence of Person-specific Biometrics in Improving Generic Stress Predictive Models," Sensors and Materials, Special Issue on Software, Algorithms, and Applications Using Sensors and Networks (Spring 2020). (in press)

[J2] G. Lopez, T. Aoki, K. Nkurikiyeyezu, and A. Yokokubo, "Model for Thermal Comfort and Energy Saving Based on Individual Sensation Estimation"Sensors and Materials, Special Issue on Software, Algorithms, and Applications Using Sensors and Networks (Spring 2020). (in press)

[J3] G. Lopez, T. Tokuda, M. Oshima, K. Nkurikiyeyezu, N. Isoyama, and K. Itao, "Development and Evaluation of a Low-Energy Consumption Wearable Wrist Warming Device," Int. J. Automation Technol., Vol.12, No.6, pp. 911-920, 2018.

[J4] Kizito Nkurikiyeyezu, Yuta Suzuki, Pierre Maret, Guillaume Lopez and Kiyoshi Itao, "Conceptual design of a collective energy-efficient and physiologically-controlled system for thermal comfort delivery in an office environment," SICE Journal of Control, Measurement, and System Integration, 11(4):312-20, (7/2018). doi:10.9746/jcmsi.11.312

[J5] Kizito Nkurikiyeyezu, Yuta Suzuki, Guillaume Lopez, "Heart Rate Variability as a Predictive Biomarker for Thermal Comfort," Journal of Ambient Intelligence and Humanized Computing, 1-13 (8/2017).
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International Conferences (peer reviewed)

[C1] Kizito Nkurikiyeyezu, Anna Yokokubo and Guillaume Lopez "Affect-aware thermal comfort provision in intelligent buildings," in proc. of the International Workshop on Social & Emotion AI for Industry SEAIxI, Cambridge, United Kingdom (Sep 2019).

[C2] Kizito Nkurikiyeyezu, Anna Yokokubo, Guillaume Lopez, "Importance of individual differences in physiological based stress recognition models," in proc. of The 15th International Conference on Intelligent Environments, Rabat, Morocco (Jun. 2019).

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[C5] Guillaume Lopez, Kazuto Takahashi, Kizito Nkurikiyeyezu, Anna Yokokubo "Development of a Wearable Thermo-Conditioning Device Controlled by Human Factors Based Thermal Comfort Estimation," in Proc. of the 12th France-Japan and 10th Europe-Asia Congress on Mechatronics (Mecatronics), Mie, Japan (09/2018). doi:10.1145/3267305.3267572

[C6] Kizito Nkurikiyeyezu and Guillaume Lopez, "Toward real-time physiologically-controlled thermal comfort provision in office," in Proc. of the 14th International Conference on Intelligent Environments (IE'18), 168-177, Rome, Italy (6/2018). doi:10.3233/978-1-61499-874-7-168

[C7] Kizito Nkurikiyeyezu, Yuta Suzuki, Yoshito Tobe, Guillaume Lopez, Kiyoshi Itao, "Heart Rate Variability as an Indicator of Thermal Comfort State," in Proc. of the SICE Annual Conference 2017, Kanazawa, Japan (09/2017).

[C8] Kizito Nkurikiyeyezu, Yuta Suzuki, Pierre Maret, Guillaume Lopez and Kiyoshi Itao, "Conceptual design of a collective energy-efficient and physiologically-controlled system for thermal comfort delivery in an office environment," in Proc. of the 2nd International Workshop on Smart Sensing Systems (IWSSS '17), Oulu, Finland (8/2017).

Local Conferences, Symposiums

[L1] Takuya Aoki, Kizito Nkurikiyeyezu, Anna Yokokubo, Guillaume Lopez, "Optimization Method of Thermal Comfort and Energy Saving Based on Individual Sensation Estimation," Proc. of Multimedia, Distributed, Cooperative, and Mobile Symposium (DICOMO2019) (Jun. 2019).

[L2] Kazuto Takahashi, Takumi Kondo, Kizito Nkurikiyeyezu, Anna Yokokubo, Guillaume Lopez, "Development of Human Factor Based Wearable Thermo-Conditioning Device," Proc. of Multimedia, Distributed, Cooperative, and Mobile Symposium (DICOMO2018) (Jun. 2018). [in Japanese]

[L3] Kizito Nkurikiyeyezu, Guillaume Lopez, "Méthode adaptative et personnalisée d'optimisation d'énergie et du confort thermique en temps réel," 3es Rencontres des Chercheurs Francophones du Kansai (RCFK 2018), Kyoto (Jun. 2018).

Awards

[A1] Aoyama Gakuin University, Doctoral Course 2019, Excellent Academic Performance Award

(other publications include 3 articles presented in peer reviewed international conferences, and 1 paper presented in local symposium)