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Deducing the classification rules for thermal comfort controls using optimal method

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ABSTRACT

This study investigates the feasibility of using a rule set of human thermal sensation index to control a heating ventilation and air conditioning (HVAC) system in order to achieve a desired thermal comfort level and energy savings. A novel approach based on an optimization method is developed to deduce the rules of learning human thermal comfort. In contrast to conventional thermal comfort levels, the proposed approach explains the linguistic rules in an “If … Then” form, in which proposed thermal comfort levels do not require an iterative solution and can be easily adjusted, depending on the specific thermal sensation of occupants. Results of this study demonstrate that the proposed thermal comfort control mechanism can also be implemented to achieve thermal comfort, energy savings, and reduce computational costs.

1. Introduction

Thermal comfort and energy consumption are of priority concern in heating, ventilating and air conditioning (HVAC) systems in an ambient intelligence environment, as evidenced by the widespread use in residence and office buildings, especially in subtropical regions. As the requirement of the occupants shifts from merely cooling to seeking a higher comfort level during the summer, thermal comfort control greatly facilitates efforts to achieve energy efficiency, necessitating the development of a control system with adaptive comfort level and energy savings.

A significant number of thermal comfort models have been developed to analyze room climates and the control design of HVAC systems [1–15]. Fanger (1973) developed a thermal comfort equation, in which comfort is determined by the response of a large group of individuals, based on six parameters (i.e., air temperature, mean radiant temperature, relative humidity, air velocity, activity level of occupants, and clothing insulation); in addition, the main indices are predicted mean vote (PMV) [2]. Zhou et al. (2014) developed a Chinese thermal sensation model because it was proved that using of existing western people-based models to predict thermal sensation of Chinese people may encounter discrepancies that cannot be neglected [4]. Meanwhile, some advanced control algorithms have been developed to enhance the performance of indoor thermal comfort [5–8,16–25]. Gruber et al. (2014) performed experiments to investigate indoor climate control in office environments by evaluating a proposed simplified model-based controller and a benchmark feed-back controller. From the investigation, it could be concluded that the simplified model-based controller primary had the possibility of reducing the energy usage associated to the ventilation system [6]. Hamdi et al. (1999) develops a method for modeling human comfort, in which the fuzzy PMV calculation does not require an iterative solution and can be adjusted, depending on the specific thermal sensation of users [5]. Wu et al. (2012) designs a gray-box numerical modeling approach to develop an empirical PMV model by using a two-stage regression structure [16]. These two-stage regression models can accurately predict PMV in both the short

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and long term. Liang et al. (2008) designs an intelligent comfort control system by integrating human learning and minimum power control strategies for the HVAC system [17]. That study integrates the variable air volume (VAV) control in the minimum power control strategy, allowing for maintenance of the thermal environment parameters in the desired range and simultaneous energy savings. Homod et al. (2012) presents a residential load factor (RLF) and Takagi-Sugeno (TS) fuzzy hybrid model to control indoor thermal comfort in a HVAC system [18]. That model significantly reduces the number of rules and number of iterations, as well as provides a small margin error. Antonino et al. (2014) demonstrates a hybrid neuro-fuzzy approach to generate the indoor temperature dynamic and feed these temperature forecasts to a fuzzy logic controller for regulating indoor temperature automatically and effectively [7]. Similarly, Ku et al. (2015) performs an adaptive neuro-fuzzy inference system (ANFIS) and a particle swarm optimization (PSO) to solve nonlinear multivariable inverse PMV model and determine a temperature set-point for controlling air conditionings [8]. The hybrid neuro-fuzzy model coupled with HVAC systems has the advantage of being characterized using linguistic rules instead of complex analytical expressions.

However, only a few of these models have been used to evaluate the efficiency of an indoor climate to produce adequate thermal conditions for occupants. Moreover, above models are subject to specific processes and complex calculations. For example, a unipolar sigmoid function is adopted for the neural network as the activation function; a multiple regression equation is relevant to the multiple variables [7,8,16]; and a membership function is adopted for the fuzzy algorithm [5,7,8,18,19].

The weaknesses of the conventional thermal comfort control mechanism are described as follows:

(i) The Fanger's PMV model involves relatively complex heat transfer processes, in which the mathematical expression is non-linear and necessitates iterative solutions (Appendix A). Owing to the inherent complexity of these processes and unavailability of certain variables, the above models are incompatible with making the designs of thermal comfort control intuitively.
(ii) Many simplified PMV models have been developed to avoid the iterative process in practical applications by using tables and diagrams [5,13,14]. These tables, diagrams, and algorithms can neither determine the relationships among the six parameters [6–8] nor identify the controlling set-points that are suitable for HVAC systems.
(iii) Some modifications of Fanger's PMV equation are made under some assumptions and simplifications, making them applicable only in appropriate conditions. The PMV calculation is inadequate for feedback controls of embedded systems, real-time systems and related applications [5,10].

To overcome these limitations, the present study proposes a method for deducing classification rules for thermal comfort controls to assist users in deploying their HVAC control strategies. The features of the proposed method are outlined as follows:

(i) It implements mining techniques [26,27] that are capable of integrating any thermal comfort standards, to learn from vast amount of environmental and physiological parameters. The proposed method induces all thermal comfort rules by using an optimization process. These deduced rules can be applied in varied thermal comfort control systems.
(ii) It deduces intuitive control rules, observes correlations between thermal comfort levels and environmental/physiological parameters for thermal comfort controls. The set-point outputs of air temperature, mean radiant temperature, air velocity and relative humidity are calculated by using the deducing rules to maintain the thermal sensation scale of the occupant's preferred PMV levels.
(iii) It generates a set of rules to predict the thermal comfort levels and initiate control strategies with simplified computations and lower computational cost, which can be used in rule-based systems, real-time controls and embedded systems with limited resources.

Fig. 1 schematically depicts a deduced-rule based control architecture for regulating thermal comfort. The aim is to deduce intuitive control rules, observe correlations between thermal comfort levels and environmental parameters (i.e., air temperature (t_a), mean radiant temperature (t_r), relative humidity (RH), and air velocity (v_a)) and the correlations between thermal comfort levels and occupant's predefined parameters (i.e., activity level (M), clothing insulation (I_{cl}), and preferred PMV) based on Fanger's model (e.g., ASHRAE Standard 55 and ISO Standard 7730) [28] for thermal comfort controls in an ambient intelligence environment. The training data sets used in this research was obtained by self-developed software for avoiding noise data. A supervised learning and classification method [27] is performed in this research for deducing control rules.

The remainder of this article is structured as follows. Section II introduces the formulation of the rule deducing model, briefly reviews the classification method for deducing rules, and outlines the design approach to deduce classification rules for thermal comfort levels by using the proposed model. Section III performs the evaluations of proposed classification model and thermal comfort control rules. Section IV presents the feasibility of applying the deducing rules to integrate thermal comfort control mechanism in order to regulate indoor environment. Section V summarizes the simulation results obtained using each proposed control strategy. Section VI discusses the features and experimental results of the proposed method. Conclusions are finally drawn in Section VII, along with a summary of the characteristics of the proposed method.

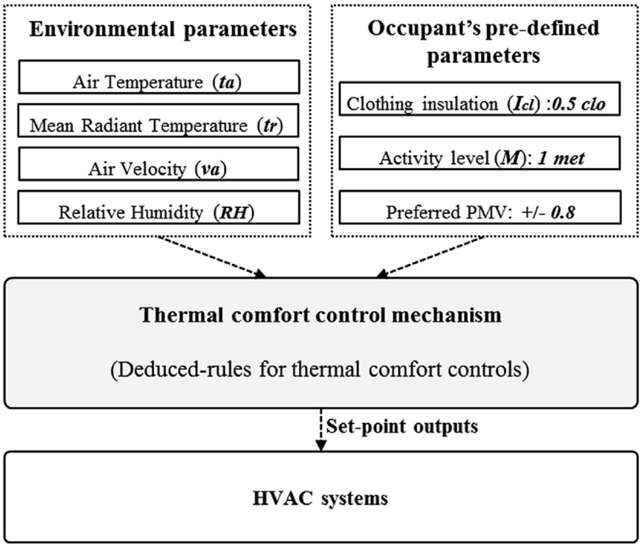

Fig. 1. Deduced-rule based control architecture for thermal comfort.