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Ali Nazım Sk. No: 30 Koşuyolu 34718 Kadıköy / İSTANBUL
Tel: 0216 327 80 10
Faks: 0216 327 79 25
www.dogayayin.com
info@dogayayin.com

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PREFACE

The 13^{th} HVAC+R Technologies Symposium organized by TTMD aimed at emphasizing the importance of climate proper system selections to attain the ultimate goal of a more sustainable built environment.

It is for this reason that 15 foreign lecturers, each of them experts in their respective fields, were invited to the symposium and delivered highly informative speeches to an audience, that consists of young professionals, students and academicians. Of course, the symposium served also as a platform for many researchers to make their contributions in relevant topics and with this book we expose them to your attention.

Interested reader is urged to look into this proceedings book, not only to see the vast possibilities of improvement of built environment by selecting climate proper systems but also to know the major potentials in the related research areas.

Dr. Murat Çakan
Head of Symposium Organizing Committee

PREFACE

On its 25th anniversary of foundation, TTMD has organized the XIIIth International HVAC+R and Sanitary Technology Symposium in Istanbul-Turkey, between 12 and 14 April 2018. This book is a collection of all presentations made and lectures given in this Symposium. The symposium was organized in a different style with more emphasis on invited lectures given by eminent scientists and professionals selected virtually from all corners of the world. The main aim was to attract all participants and presenters in the same hall in order to facilitate the share of up-to-date and innovative information and research among all participants in a collective and simultaneous manner. This technique proved to be a success according to several evaluations being made and many positive comments received. Of course, this approach did not neglect oral and poster presentation, which were carefully integrated to the main focus and the theme of the Symposium, namely *Climate Proper HVAC System Solutions*. This theme did fit very well with the current decarbonization efforts, issues and concerns about high-rise buildings, and a negative trend of using same style and structure of buildings almost in every geographic region and climate. Speakers have instead emphasized that climate is a very important factor in the design, selection of systems and equipment, construction, commissioning, and finally, the operation. Several examples were given in order to lay out a concrete road map for climate-sensitive HVAC design and architecture.

The Symposium shed influential light on global decarbonization and emphasized the importance of HVAC+R within the quest of decoupling CO_2 emissions from sustainable development of nations. Indeed, buildings need to be climate aware, sensitive, and responsive. In this token, it was very timely to discuss the potential impact of HVAC+R systems on the climate change and to collectively find robust, sustainable, and rational solutions beyond the so-called smart buildings. We need to widely expand our vision from single buildings to complete sets of the built environment at different scales and focus more deeply on the interactions of human activities with the environment at large. In this respect, renewable energy resources and rational use of these resources collectively in an optimum mix at district scale are becoming more and more important for the building sector, along with better and concerted utilization of fossil fuels -if needed- with systems and equipment like cogeneration coupled with heat pumps and low-exergy heat distribution and collection systems, like chilled beams in a hybridized form.

This book is an elaborated collection of all lectures and presentation on record from the Symposium. I invite you to read all papers and contact us for a wider and concerted networking, in a continuous and productive discussion platform for today and for the future of humankind within the context of Paris agreement signed by a vast majority of countries. I hereby invite remaining few -in quote developed-countries to join, who seem to be quite unaware or negligent of the urgency of global warming.

Last but not least, I warmly thank to all members of the Organizing Committee, our TTMD members, the Symposium staff, who all worked meticulously over several months in order to realize this Symposium in its best format and content, and finally produced this archival foundation for the international scientific and professional community. I sincerely hope that this publication will enhance and positively provoke innovative solutions and facilitate scientific collaboration for the benefit of environment and humankind.

Please join us in the quest of building better and more climate rational buildings and cities in a context of not only smart but also rational in terms of energy and exergy. Let’s make the success of this Symposium permanent for today and for tomorrow together!

Prof. Dr. Birol Kılkış
President of TTMD and Symposium Chair

Personalized Thermal Comfort Driven Control Techniques in Hvac Systems

Cihan TURHAN, Silvio SIMANI**, Gülden GÖKÇEN AKKURT*

* *Department of Mechanical Engineering, Faculty of Engineering, Izmir Institute of Technology, Gulbahce Campus*

** *Department of Engineering, University of Ferrara. Via Saragat 1E - 44122 Ferrara (FE), Italy, ICT Campus*

silvio.simani@unife.it

SUMMARY

The Heating, Ventilating, and Air Conditioning (HVAC) control systems traditionally use thermostats, expending energy freely to achieve a given set point. Intelligent controllers which use programmable thermostats are smarter and allow users to vary set points by time of the day and day of the week. Nevertheless, none of these control systems are aware of user comfort: they focus, instead, only on controlling room temperature. Participation of the buildings' occupants is essential in learning their comfort profiles as personalized thermal comfort driven HVAC operations do. Studies conducted in the last decade showed that while intelligent HVAC control systems can greatly improve thermal comfort, energy consumption reduction, health, satisfaction and productivity. Personalized thermal comfort driven control is the most effective way of both saving energy and maintaining thermal comfort. This paper provides a detailed review of HVAC control techniques from traditional controllers towards personalized thermal comfort driven controllers. Meanwhile, the paper appraises recent advanced techniques on the design and control of personalized HVAC systems. As an application and case study, a personalized thermal comfort driven controller which is being developed in Izmir Institute of Technology will be introduced and the preliminary results will be discussed.

INTRODUCTION

Thermal comfort is perceived as the comfort of occupants under given thermal environment conditions and body sensation which is the function of six parameters: indoor air temperature (Ti), relative humidity (RH), air velocity (va), clothing insulation (clo), metabolic rate (met) and mean radiant temperature (MRT) [1]. Predicted Mean Vote (PMV) is the most common metric to estimate the thermal comfort as presented in ASHRAE 55 Standard [1]. PMV uses six parameters for the calculation and refers to a thermal scale that runs from cold (-3) to hot (+3), originally developed by Fanger [2] and later adopted as ISO 7730 Standard [4]. The scale using codes in Table 1 as -3 for cold, -2 for cool, -1 for slightly cool,0 for neutral, +1 for slightly warm, +2 for warm and +3 for hot. According to the ISO 7730 Standard [3] the values of PMV is 0 with a tolerance of ± 0.5 as a good thermal comfort.

Table 1. Thermal sensation scale in ISO 7730 [3].

Thermal sensations	PMV
Hot	+3
Warm	+2
Slightly warm	+1
Neutral	0
Slightly cool	-1
Cool	-2
Cold	-3

Predicted Percentage of Dissatisfied (PPD) is another thermal comfort index which predicts the percentage of occupants that will be dissatisfied with the thermal conditions. If 90% of the occupants are satisfied (or 10% dissatisfied) with their thermal environment, then the ISO 7730 Standard [3] classifies an environment as thermally acceptable.

Along with the conventional PMV-PPD index for buildings which use HVAC equipment, the adaptive thermal comfort model [4] was adopted in AHSRAE 55 Standard [1] for natural ventilated buildings. The model assumes that, if changes occur in the thermal environment to produce discomfort, the occupants generally change their behavior and act in a way that the occupants restore their comfort [5]. Besides the researches on adaptive thermal comfort, a study by de Dear and Brager [6] showed that each occupant has different thermal preferences depending on age, gender and morphology. Therefore, to obtain the most satisfying thermal comfort with energy efficiency becomes a challenge for HVAC system control.

HVAC systems mostly use conventional control logic like On/Off and conventional Proportional-Integral-Derivative (PID) methods and real-time temperature measurements without considering thermal comfort of occupants. Artificial Intelligence (AI)-based HVAC control systems can detect thermal comfort, however, they require complex model of the HVAC system along with thermal comfort model. Although the control algorithms of HVAC systems are directly applicable, determination of thermal comfort is still a problem. Furthermore, AI-based controllers merely calculate a unique standardized thermal sensation or operative temperature for all occupants, without giving them any direct feedback possibilities [7]. Individual differences or preferences can be accommodated with personalized thermal comfort driven controllers. Occupant satisfaction and productivity can also be increased as a result of improved personalized thermal comfort and control over the HVAC systems.

In this paper, a review of HVAC control techniques from conventional controllers towards personalized thermal comfort driven controllers is provided. Moreover, a personalized thermal comfort driven controller which is being developed in Izmir Institute of Technology is introduced and the preliminary results are given.

HVAC CONTROL SYSTEMS

HVAC control systems have been investigated by various techniques such as standard On/Off control, PID-type control and AI-based control methods like Artificial Neural Network (ANN), Artificial Neuro-Fuzzy Inference System (ANFIS), Fuzzy Logic (FL) and Model Predictive Control (MPC) approaches and summarised in Table 2.

Table 2. HVAC control systems.

Type of Controller	Method	Year	Output variable	Advantages	Disadvantages	References
CONVENTIONAL CONTROLLERS	On/Off	1930s	Temperature	Simple and common	No feedback	[8-12]
	PID-type	1980s	Temperature	Easy to operate	Do not produce fast response, suffer a problem of overshoot, large settling time	[13-16]
AI-BASED CONTROLLERS	ANN	1990s	Thermal Comfort	Requires mathematical model of both HVAC system and thermal comfort sensation	Difficult to find proper construction of layers and neuron numbers	[17-20]
	FL	1990s	Thermal Comfort	Preferable for HVAC systems that are hard to model and control mathematically	Requires time and experts to construct rules	[21,22]
	ANFIS	1990s	Thermal Comfort	Self-learning ability simple structure	Combination of ANN and FL disadvantages	[23-25]
	MPC	2000s	Thermal Comfort	Anticipate future events, optimization procedure	Require building models, Difficult to apply in larger buildings	[26-29]

PERSONALIZED THERMAL COMFORT DRIVEN CONTROL

Individual differences are neglected in conventional PMV-PPD method. However, studies in literature show that individual differences such as gender and age are significant on thermal comfort [30,31]. Conventional HVAC system controllers merely regulate the indoor air temperature where thermostats are used for the feedback control of temperature. But the controllers do not detect the occupant's thermal comfort. On the other hand, AI-based controllers calculate a unique standardized thermal sensation or operative temperature for all occupants instead of taking into account individual differences. Therefore, researchers have started exploring the ways and methods to make HVAC systems adaptive to the occupant's thermal sensation and individual differences instead of using average models. In 2003, Lin et al. [32] developed a thermal comfort control model by using multi-sensors for HVAC systems. The study addressed this multi-sensor, single-actuator control problem which was solved by a computer program and optimization technique. In the study, each room equipped with multi-sensors and a sensor network and the controller operated only on the temperature reading from the room sensors. As a conclusion, the authors demonstrated that the comfort-optimal strategy reduces energy consumption by 4% while reducing PDD from 30% to 20%. Occupancy measurements play an important role to achieve energy saving and thermal comfort. Brooks et al. [33] used motion detectors with low-cost, wireless sensor nodes. A building in University of Florida campus which uses 3 AHUs, was selected as a test chamber. The controller consists of a wireless sensor network (Fig.1a), a software infrastructure for data management, control execution (MATLAB) and a control algorithm for computing commands. A Passive Infrared (PIR) sensor (for measuring occupant presence) and a T/RH sensor were deployed with a microprocessor to collect real-time measurements. The experiments showed that the controller achieved 37% energy saving without scarifying thermal comfort. In 2014, Jazizadeh et al. [34] implemented occupant thermal comfort profiles to the HVAC control logic which is called personalized thermal comfort driven control. The estimation of the profiles was applied by FL approach. The controller used user interference and thermal preference scale (Fig1b). Participatory sensing approach which relies on computing devices such as notebooks and mobile phones, were adapted to the study and occupants reported their preferences under different indoor environmental conditions through the user interface. Thus, the controller learned occupant's thermal comfort profiles which are used in HVAC control. Moreover, the results showed a 39% reduction in daily average airflow when the HVAC system used personalized thermal comfort driven controller.

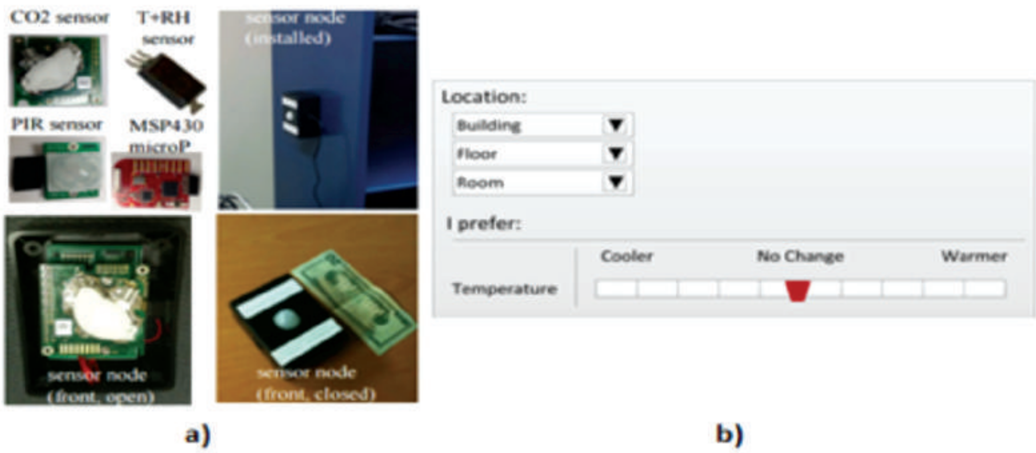

Figure 1. *(a) Wireless sensors [33], (b) User interface of thermal preference scale [34].*

In another study by Erickson et al. [35], Power-efficient Occupancy-based Energy Management System was developed. The HVAC system was controlled based on actual occupancy levels and utilizes a purpose-built wireless network of camera sensors with a parallel network of PIR sensors to sense the presence of occupants to find the optimal personalized thermal comfort. Some of the researches preffered localized thermal comfort control instead of large control systems [35, 36]. Watanabe et al. [36] used a chair with local heating and cooling strips and fans to ensure personalized thermal comfort (Fig.2a). Authors concluded that even at a room temperature of 30oC, the occupants were able to create acceptable thermal environments by using the chairs with fans. Lopez et al. [37] achieved personalized thermal comfort by heating wrist instead of heating the whole thermal environment (Fig.2b). The authors indicated that the personalized thermal comfort controller which consumes less energy could be used instead of conventional control systems.

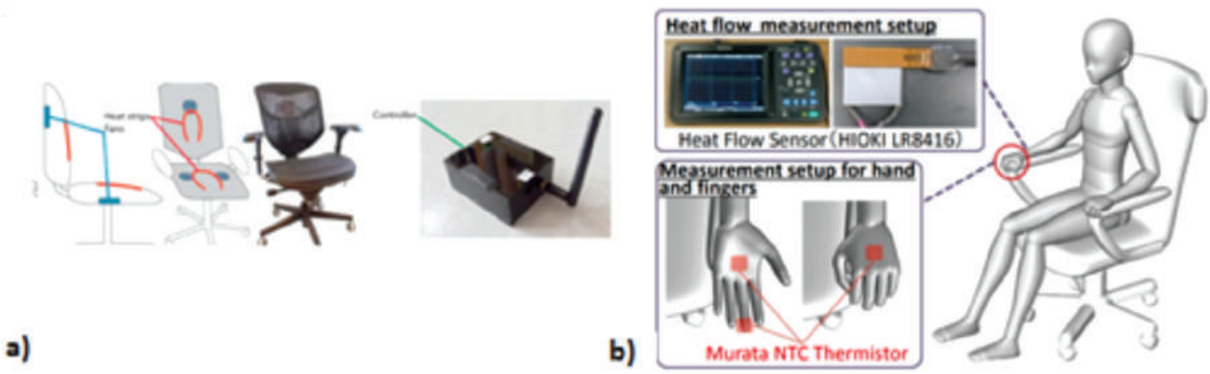

Figure 2. *Examples of personalized thermal comfort controllers.*

Wearable sensors are becoming more common in prediction of personalized thermal comfort. For instance, Fieldmeier [38] developed a portable wearing thermal comfort system (Fig.3) where the sensors are located on finger (rings), wrist (watches), neck (necklaces), chest (necklaces) and shirt exterior (pendants). The system was worn and trained by a single user in order to learn the preferences of its owner. These comfort signals were then used to control the HVAC system.

Figure 3. *Wearable sensors used for personalized thermal comfort [38]*

Ranjan and Scott [39] used thermographic imaging technique for personalized thermal comfort control. The controller used real-time thermal preferences of the occupants by machine learning model (Fig.4a). The authors indicated that energy could be saved if realtime thermal preferences were used rather than using standard air temperature based control in HVAC systems. Similarly, Ghahramani et al. [40] utilized infrared thermography with the help of sensors which is installed on eyeglass frame (Fig.4b). The authors proposed a hidden Markov model learning approach to capture dynamic thermal comfort of occupants. Surveys were conducted for four days at the same time with the measurements and the proposed learning algorithm predicted uncomfortable conditions with an accuracy of 82.8%. The authors concluded that real-time measurements of personalized thermal comfort allows HVAC system controllers to optimize energy consumption while ensuring better thermal comfort.

Figure 4. *(a) Thermographic data collection points [39], (b) the infrared sensing system installed on an eyeglass frame [40].*

CASE STUDY

As an application and case study, a new real time personalized thermal comfort driven control system is being developed in a case building in İzmir Institute of Technology, İzmir, Turkey. The objective of the controller is to maintain a particular comfort level based on objective sensor measurements, subjective occupant data and its control over the operation of an air conditioner. The controller consists of temperature/RH sensor, O2 sensor and PMV sensor to make real-time measurements, microcontrollers to communicate among the devices (Fig.5a), a mobile application to obtain subjective thermal comfort preferences of the occupant (Fig.5b), a server to control all the systems, an actuator and an IR sensor to control the actuator remotely.

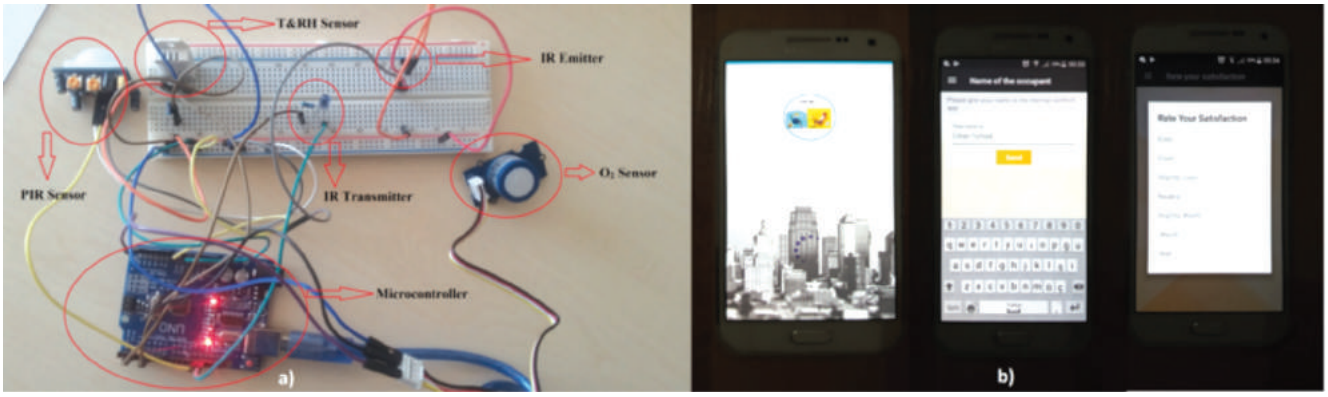

Figure 5. The developed personalized thermal comfort driven controller a) Sensor network b) Mobile application

With the mobile application, the controller learns the thermal preference of the occupant, then, controls the future actions of air conditioner according to thermal preference of the occupant. A fuzzy logic model predicts the future desired thermal comfort preferences of the occupant following a day training period. Moreover, low-cost digital sensor network implements the real-time PMV calculation and directs the data to the controller (Fig.6).

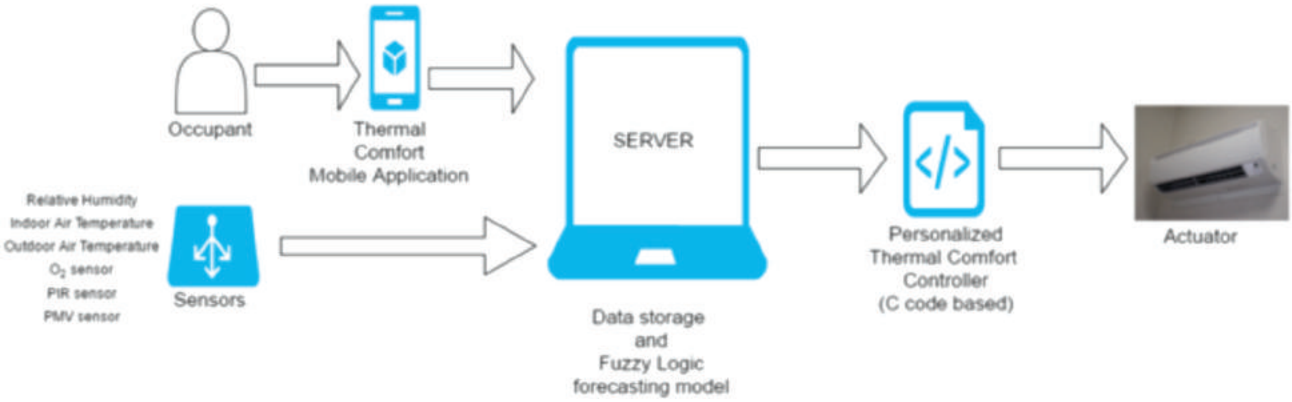

Figure 6. The developed personalized thermal comfort controller

The developed personalized thermal comfort driven controller was tested from July 3rd, 2017 to December 3rd, 2017 and compared with conventional PID controller of air conditioner in the case building. The developed controller decreased the electricity consumption by 8.2% compared to the PID controller whilst achieving better thermal comfort.

CONCLUSIONS

The personalized HVAC system aims to provide a comfortable and healthy environment locally and with respect to individual need of the users. Beside comfort improvements, personalized HVAC controllers also reduce energy consumption due to higher effectiveness compared to conventional HVAC design. The studies in this paper showed that personalized HVAC systems can save the energy up to 40%. For a case study and application, a new personalized thermal comfort driven controller was developed in Izmir Institute of Technology. The controller was tested for 5 months and compared with the conventional PID controller. The results showed that the developed controller decreased electricity consumption by 8.2% while achieving better thermal comfort.

Though the development and application of new sensors, this review indicates that a better understanding of occupants in the controller level can enhance the robustness of the personalized HVAC systems.

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