Title	Energy efficient thermal comfort control for cyber-physical home system
Author(s)	Cheng, Zhuo; Shein, Wai Wai; Tan, Yasuo; Lim, Azman Osman
Citation	2013 IEEE International Conference on Smart Grid Communications (SmartGridComm): 797-802
Issue Date	2013-10
Type	Conference Paper
Text version	author
URL	http://hdl.handle.net/10119/12368
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Description	

Energy Efficient Thermal Comfort Control for Cyber-Physical Home System

Zhuo Cheng, Wai Wai Shein, Yasuo Tan and Azman Osman Lim
School of Information Science
Japan Advanced Institute of Science and Technology
1-1 Asahidai, Nomi, Ishikawa 923-1292, JAPAN
Email: {chengzhuo, waiwaishein, ytan, aolim}@jaist.ac.jp

***Abstract*—Technology advances allow us to design smart home system for the purpose to achieve high demands on occupants' comfort. In this research, we focus on the thermal comfort control (TCC) system to build an energy efficient thermal comfort control (EETCC) algorithm, which is based on the cyber-physical systems (CPS) approach. By optimizing the actuators; air-conditioner, window and curtain, our proposed algorithm can acquire the desired comfort level with high energy efficiency. Through the raw data from experiments, we evaluate and verify our proposed algorithm in the cyber-physical home system environment by using MATLAB/Simulink software.**

I. Introduction

Nowadays, the advanced technology allows us to live in a more comfortable and smart environment. At the same time, the demands such as: comfort, control and energy efficiency increase speedily. The improved heating, ventilation and air-conditioning (HVAC) system and control design strategies can offer numerous opportunities to meet those demands within efficient energy cost. In this research, we present a cyber-physical systems (CPS) based thermal comfort control (TCC) system which is combined with Proportional-Integral (PI) and supervisory controller using an energy efficient thermal comfort control (EETCC) algorithm. Predictive Mean Vote (PMV) index is adopted to evaluate home thermal comfort level. We correlate the home thermal environment with multiple actuators, which are defined as objects that can potentially change the home thermal environment. Our proposed TCC system enables to monitor and maintain the desired PMV value dynamically with three actuators: air-conditioner, window and curtain.

The control of thermal comfort for home environment is a challenging task for the reasons of (*i*) the dynamic change of outside environment, which can be used as one of the thermal resources for controlling the home thermal comfort; and (*ii*) the preference of thermal environment for each occupant is different. To challenge these points, CPS can be one of the potential approaches. CPS in [1], [2] is defined as a tight integrations of computation, communication, and control for active interaction between physical and cyber elements in which embedded devices, such as sensors and actuators, are wireless or wired networked to sense, monitor and control the physical world. In our TCC system, we use the idea of design and implementation of cyber-physical control systems over the wireless sensor and actuator network (WSAN) and the feedback control architecture presented in [3]. In our model, the thermal environment factors (e.g., temperature, air speed, etc.) are continuously sensed by different kinds of sensors and the sensed data is spatial averaged and used to generate the PMV index, which is used to compare with the desired value. Then, the EETCC algorithm decides the appropriate control signals to active different actuators according to the difference between the current and target PMV value and the additional environment factors. Following this, the PI controller inside air-conditioner figures out the preferred setting temperature in case of the air-conditioner is triggered by the supervisory controller. In TCC system, only the air-conditioner is designed with PI controller.

Some related works of thermal comfort control in home environment can be found in [4], [5], [6], [7] and [8]. Schumann et al. [4] presents a case-based reasoning approach for computing distribution of the thermal sensation of occupants for arbitrary environmental conditions. It provides a significant assistance to the building operator for its task of resolving the tradeoff between occupant comfort and energy efficiency. Oliveria et al. [5] presents a load management mechanism that allows inhabitants to adjust power consumption according to expected comfort and energy price variations. Molina et al. [6] presents an optimization and control algorithm for residential temperature regulation. Concepts from system identification, model predictive control and genetic algorithms are incorporated compromise between comfort and cost in the presence of time-varying electricity prices. Wang [7] presents a ventilation control strategy for multi-zone variable air volume air-conditioning systems and an adaptive optimization algorithm for optimizing the fresh airflow rate to minimize the energy consumption. Vazquez et al. [8] proposes a smart home application based on habit profiles for thermal comfort support. It purses to keep the environment as close as possible to the desired air quality and thermal comfort conditions by means of low energy cost strategies taking into account the management of shading devices, automated windows and dampers.

Unlike these works however, this research aims to develop the practical application of CPS approach for TCC system with multiple actuators in home environment. The contribution of this research is divided into three folds: (*i*) to present the TCC system with three actuators along with the supervisory controller, which is designed in an energy efficient way by using natural resources; (*ii*) to introduce a thermal comfort simulator implemented in MATLAB/Simulink environment for a residential home; and (*iii*) to the best of our knowledge, our research contributes the whole picture of monitoring the TCC system to achieve different occupants' comfort preferences using the MATLAB/Simulink software via the raw experiment data obtained from our intelligent home environment system.

The rest of this paper is structured as follows. Research background related to this paper is described in Section II. In Section III, we describe the design and modeling of the TCC system, and explain the proposed EETCC algorithm that is used in the supervisory controller. To evaluate our proposed TCC system, some simulation studies are carried out in Section IV. Some relevant conclusions and our future works are drawn in Section V.

II. Research Background

A. Thermal Comfort

Thermal comfort is that condition of mind that expresses satisfaction with the thermal environment [9]. A thermally comfortable home environment makes for occupant health and comfort. Control system based on thermal comfort can much more significantly improve building energy efficiency than ones maintaining one or more of thermal factors like air temperature, humidity, and air speed at a constant level. Improving thermal comfort and designing its control system have now become an important concern.

1) Predictive Mean Vote (PMV): In this paper, PMV index, which is proposed by Fanger [10], is used to evaluate thermal comfort level. It is now most widely used index and adopted by ISO standard [11]. The PMV predicts the mean value of the votes of a large group of persons on the 7-point thermal sensation scale (as listed below), based on the heat balance of the human body. Thermal balance is obtained when the internal heat production in the body is equal to the loss of heat to the environment [11].

1) +3 Hot
2) +2 Warm
3) +1 Slightly warm
4) +0 Neutral
5) -1 Slightly cool
6) -2 Cool
7) -3 Cold

The value of PMV can be calculated for different combinations of six primary factors affecting the thermal comfort level as listed below. The equation for calculating PMV index can be found in [11].

1) Metabolic rate
2) Clothing insulation
3) Air temperature
4) Mean radiant temperature
5) Air speed
6) Relative humidity

2) Predicted Percentage Dissatisfied (PPD): The PMV index predicts the mean value of the thermal votes of a large group of people exposed to the same environment. But as there are large variations, both physiologically and psychologically, from person to person, it is difficult to satisfy everyone in a space [11]. The environmental conditions required for comfort are not the same for everyone. It is meaningful to be able to predict the number of people likely to feel uncomfortably warm or cool. The PPD is the index that establishes a quantitative prediction of the percentage of thermally dissatisfied people who feel too cool or too warm. With the PMV value determined, calculate the PPD using equation:

$$PPD = 100 - 95 \cdot exp(-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2) \quad (1)$$

3) Draught: The PMV and PPD express warm and cold discomfort for the body as a whole. But thermal dissatisfaction can also be caused by unwanted cooling or heating of one particular part of the body, which is known as local discomfort [11]. The most common cause of local discomfort is draught. The discomfort due to draught may be expressed as the percentage of people predicted to be bothered by draught. We can calculate the draught rate (DR) using equation:

$$DR = (34 - t_{a,l})(\overline{v}_{a,l} - 0.05)^{0.62}(0.37 \cdot \overline{v}_{a,l} \cdot Tu + 3.14) \quad (2)$$

For $\overline{v}_{a,l} < 0.05$ m/s, use $\overline{v}_{a,l} = 0.05$ m/s, $DR > 100\%$, use $DR = 100\%$. Symbol $t_{a,l}$ is the local air temperature in degrees Celsius 20°C to 45°C; $\overline{v}_{a,l}$ is the local mean air velocity in metres per second; Tu is the local turbulence intensity in percent, 10 % to 60 %. The model applies to people at light, mainly sedentary activity with a thermal sensation for the whole body close to neutral and for prediction of draught at the neck.

B. Cyber-physical Systems (CPS)

CPS is integrations of computation and physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa [12]. It is believed that in both the academic and industrial communities that CPS will have great technical, economic and social impacts in the future. In recent years, CPS has been becoming a very active research filed for engineers and researchers. Some researches of CPS application about control system for home environment can be found in [13], [14], and [15]. Lai et al. [13] proposes the OSGi-based service architecture for cyber-physical home control system, which supports service-oriented control methods. Rajhans et al. [14] introduces an extension of existing software architecture tool, called AcmeStudio, for the modeling and analysis of CPS at the architecture level. By defining three entities; the cyber domain, the physical domain and their interconnection, they illustrate the architectural modeling using CPS architecture style with the example of a temperature control system for two zones (rooms). The CPS applications in [15] includes medical devices and systems, assisted living, traffic control and safety, advanced automotive systems, energy conservation, and smart structure.

III. Thermal Comfort Control System

A. System Architecture

Fig. 1 shows the basic architecture of TCC system. In this architecture, cyber world and physical world are defined. To connect these two worlds, we use a communication network of WSAN, which comprises of two components: sensors and actuators. The sensors in the physical side send the environment factors periodically to supervisory controller in the

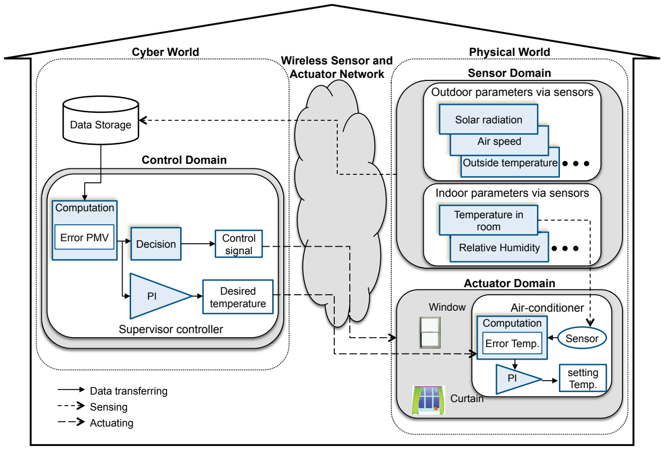

Fig. 1: Thermal comfort control (TCC) system

TABLE I: States of TCC system

Status	*Air-conditioner*	*Window*	*Curtain*
State 0	#	#	#
State 1	#	#	○
State 2	#	○	#
State 3	#	○	○
State 4	○	#	#
State 5	○	#	○

means OFF/close; ○ means ON/open

cyber side. Subsequently, the supervisory controller computes an error PMV value that is a difference value between current PMV value and the desired PMV value. Based on the error PMV value, the supervisory controller figures out a control signal to active appropriate actuators (air-conditioner, window and curtain) to perform the corresponding tasks to adjust the home thermal condition. The operation of window and curtain is just opening or closing, but when air-conditioner is triggered, two steps are needed for controllers to generate a control input. First, supervisory controller figures out the desired room temperature according to the error PMV value and environment factors by using a PI controller and sends it to the air-conditioner. Second, based on the value of desired room temperature, the controller in air-conditioner computes an error temperature that is a difference value between current temperature and desired temperature and sends it to the inside PI controller. According to the value of error temperature, the PI controller generates a setting temperature as a control input signal to operate air-conditioner.

B. State Description

The TCC system is organized in a set of six states, which is represented as numerical number 0-5 respectively, shown in TABLE I. As the reason of energy efficiency, turning on the air-conditioner and opening the window and/or the curtain at the same time is not allowed in our system.

C. Mathematical Representation

When PMV is adopted to evaluate room thermal comfort level, four types of environment factors need to be taken into account.

1) Air Temperature: A dynamic room temperature equation can be represented as:

$$\frac{dT_r}{dt} = \frac{1}{\beta}\sum Q \tag{3}$$

where the T_r is the room temperature, t is the time, β is the product of air density, room volume, and air specific heat capacity, Q means the room heat gain.

Here, we consider five types of heat that makes the changes of room temperature; heat gain from the air-conditioner (Q_{aircon}), heat convection from opening the window ($Q_{convection}$), heat conduction due to temperature difference between inside and outside through window ($Q_{conduction}$), heat gain due to solar radiation through window ($Q_{radiation}$) and the sensible heat gain by occupants ($Q_{occupant}$). The equation used to calculate the heat value is explained in our previous research [16].

2) Mean Radiation Temperature: The mean radiation temperature is calculated by using the equation:

$$\overline{T}_r^4 = \sum_{i=1}^{6} T_i^4 F_{p-i} \tag{4}$$

where, $\overline{T}_r$ is mean radiant temperature (°C), T_i is the surface temperature (°C) of the wall i , F_{p-i} is the angle factor between occupant and surface i.

The angel factor depends on the position and orientation of the person, we use the ASHRAE Thermal Comfort Tool (Version 2) to calculate the angel factor based on our room architecture. The surface temperature for each wall is the sum of air temperature and a corresponding correction factor for each wall. The correction factor is based on our former experiments and the value is shown in TABLE II.

3) Air Speed: In this paper, we ignore the air flow due to the person moving around, and attach the correction factor to the room air speed, which is multiplied with the sensed outside air speed, corresponding to different states. The correction factor is based on our former experiments and the value is shown in TABLE II.

4) Relative Humidity: As the influence of relative humidity on thermal sensation is small when the indoor environment is close to thermal comfort level. We may usually ignore the variation of this parameter when determining the PMV value. In this paper, we set a typical value to relative humidity as shown in TABLE II.

D. Supervisory Control

The supervisory controller using EETCC algorithm decides which kind of the actuators should be active at each time instant. The control signals are determined based on the proposed control algorithm. In our method, in order to use nature resource to reduce energy cost, we prefer to choose states without using air-conditioner. Every time we choose the state that can mostly yield occupants neutral thermal feeling. If none of the states without using air-conditioner can meet the thermal comfort demands, which are judged by DR_{th} and PMV_{th}, the threshold values for $dr()$ and $pmv()$ function, we need to choose the states using air-conditioner. The function $dr()$ is based on the equation (2) and function $pmv()$ has six input parameters as described in section II.

In TABLE I, we can see that the conditions for window and curtain are the same in state 0 and 4. Similarly, state 1 and 5 also maintain the same conditions. First we should choose from state 0 and 1. If state 0 is chosen, the system shifts to state 4, otherwise to state 5. The amount of heat gain is different between state 0 and 1. By computing current room PMV value, system can know the temperature is higher or lower than desired value, which can be used to distinguish the two states. In addition, in order to avoid actuator frequent operation we have designed a $timer$ to count how long the current state has been holding.

The other symbolic used in algorithm are: cs means output control signal, ps means system state at previous time. $Time_{th}$ means the minimum time that the state has to be held for both on and off cases. We defined a function f_{si}, corresponding to state i. The input of the f_{si} is the sensed outside environment factors: air speed, air temperature, solar radiation and the output of f_{si} is corresponding room air speed (v_i), and room heat gain (Q_i). The output value is stored in the set of F, of which the element is two-tuples constituted by v and Q. We use f_i to represent the ith element of F and $tr, \bar{t}_r, r, m, c$ to represent the parameters: room air temperature, mean radiant temperature, relative humidity, metabolic rate, clothing insulation.

Algorithm 1 EETCC

if $timer < Time_{th}$ **then**
  $cs := ps$
end if
for all $f_i \in F$ **do**
  if $dr(v_i, t_r) < DR_{th}$ and $\left|pmv(v_i, t_r, \bar{t}_r, r, m, c)\right| < PMV_{th}$ **then**
    $value := \left|pmv(v_i, t_r, \bar{t}_r, r, m, c)\right|$
    $S := S \cup \{(i, value)\}$, where i is the index of f_i
  end if
  if $|S| > 0$ **then**
    $i := min(S)$, where min returns the index i of the minimum $value$ of elements in S
    $cs := s_i$
  else
    $S' := \{(0, Q_0), (1, Q_1)\}$
    if $pmv(v_i, t_r, \bar{t}_r, r, m, c) > 0$ **then**
      $i := min(S')$, where min returns the index i of the minimum Q of elements in S'
    else
      $i := max(S')$, where max returns the index i of the maximum Q of elements in S'
    end if
    $cs := s_{i+4}$, where s_{i+4} is the appropriate state using air-conditioner
  end if
end for

IV. Simulation Studies

A. Simulation Environment and Setup

In this section, we verify and examine how the proposed TCC system will behave in physical world by making simulations conducted with MATLAB/Simulink tool. In the simulations, we use the raw data from the experiments that were conducted at the intelligent house environment, *iHouse* (Fig. 2), which is located at Nomi city, Ishikawa, Japan. We choose the two days experimental data, one is in autumn (28th October 2012) and the other is in summer (2nd August 2012), to represent the two kinds of different outside environment condition, good and bad weather, respectively. The judgment for outside weather condition is based on the sensed data (e.g., air speed, air temperature and solar radiation). The data we used in simulations is conducted at the iHouse master room, in which user is expectedly used for work and study. These activities pertain to sedentary physical activity levels, which belong to the application scope of [11]. One Mitsubishi air-conditioner is equipped in the room, which is controlled by a PI controller. The PI gains are tuned by using Simulink control system toolbox. The values and parameters used in simulations are shown in TABLE II.

TABLE II: Simulation parameters and settings

Parameter	*Value*
$V_{room}(L \times W \times H)$: volume of room	5.005m ×4.095m ×2.4m
K_p^{sup}: P for PI in supervisory controller in state 4 & 5	12.6435, 7.89
K_p^{air}: P for PI in air-conditioner in state 4 & 5	13.3234, 8.83
K_i^{sup}: I for PI in supervisory controller in state 4 & 5	0.06567, 0.0453
K_i^{air}: I for PI in air-conditioner in state 4 & 5	0.08263, 0.0645
$Time_{th}^{on}$: for using air-conditioner	5 min
$Time_{th}^{off}$: for not using air-conditioner	3 min
m: metabolic rate	1.0 met
c: cloth insulation for summer & autumn	0.6 clo, 0.7 clo
r: relative humidity	30 %
C_{air}: air speed CF for states 0 – 5	0, 0, 1.0, 0.8, 0, 0
C_w^{Aut}: temperature CF for wall 1 – 6 Autumn	0, 0,-0.5,-0.5, 0, 0
C_w^{Sum}: temperature CF for wall 1 – 6 Summer	1, 1, 3, 3, 0, 0
F_{p-i}: angel factor btw occupant and wall 1 – 6	0.13, 0.03, 0.04, 0, 0.1, 0.18
P = proportional gain; I = integral gain;	CF = correction factor

TABLE III: Categories of thermal comfort demands

Category	*PPD (%)*	*PMV*	*DR (%)*
A	< 6	-0.2 < PMV < +0.2	< 10
B	< 10	-0.5 < PMV < +0.5	< 20
C	< 15	-0.7 < PMV < +0.7	< 30

B. Simulation Results

To evaluate our proposed TCC system, we conduct simulations in two different kinds of outside environment. The day we choose in autumn represents the good weather that the environment factors are appropriate to be used to maintain indoor thermal comfort naturally. The day we choose in summer stands for the bad weather, which natural resources can little be used to maintain room thermal comfort, which results the strong depending on the regulation of air-conditioner. We have done simulations for three different demands of the thermal comfort, shown in TABLE III, which is according to the recommendation in [11].

Fig. 3 and 4 show the control results of the PMV-PPD index for the thermal comfort demands of category B. The

Fig. 2: Experiment intelligent home environment – iHouse

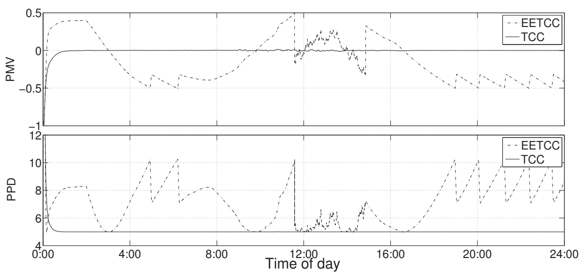

Fig. 3: PMV-PPD in autumn

PPD is calculated according to the PMV value based on the equation (1). The symbol EETCC in Fig. 3 and 4 stands for the result under the EETCC algorithm and TCC represents the thermal comfort control system only using air-conditioner to maintain the room thermal comfort leaving curtain and window closed. In these figures, all index values are in line with the thermal comfort requirements. The pmv results controlled by EETCC vary within the comfort zone which is between the range of -0.5 and +0.5. The pmv index value in Fig. 3 usually changes not quickly but a relative sudden decrease happened near 12 o'clock which is caused by the opening of windows. As the wind from outside can increase the air velocity around person in room quickly, it affects the person thermal comfort obviously. The main difference between Fig. 4 which shows the result of relative bad weather and Fig. 3 is the existing of periodic cycles between the upper and lower limit of PMV. The cycles are caused by the air-conditioner periodic regulation. When the quality of outside environment factors are far from the demands of maintaining home environment thermal comfort, the indoor PMV value will soon approach the upper limit when only using natural resources. Subsequently, the air-conditioner will start to regulate the room environment to maintain it in comfort zone. In order to prevent frequent ON/OFF operation of air-conditioner, whenever air-conditioner starts to work, it controls the PMV value to close the lower limit.

Fig. 5 and 6 show the outside environment factors. These factors as a whole decide how much we can use the natural resource to maintain the room thermal comfort. If the outside weather is appropriate to maintain indoor thermal comfort, TCC system will use the natural resource rather than using

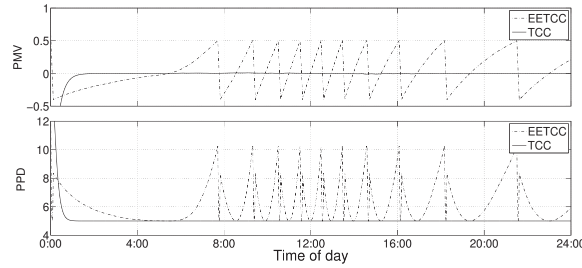

Fig. 4: PMV-PPD in summer

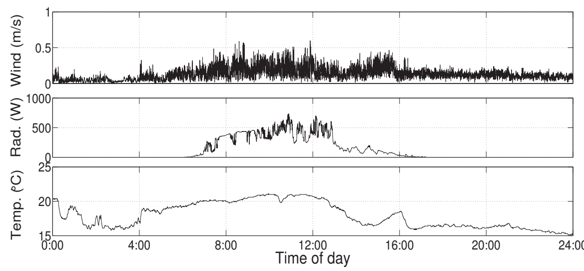

Fig. 5: Environmental factors in autumn

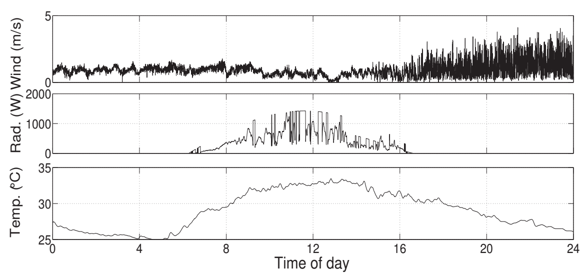

Fig. 6: Environmental factors in summer

air-conditioner. By this way, the energy cost is reduced. The Fig. 7 and 8 show the system states occupancy distribution. The state is decided by the supervisory controller according to the EETCC algorithm. For good weather, the system seldom turns to the state using air-conditioner and as the environment factors are moderate, it results the system almost staying in one state as shown in Fig. 7. But for bad weather, the state distribution is not always centralized in one particular state and air-conditioner has been much more used as depicted in Fig. 8. Fig. 9 and 10 show the energy consumption for different categories (A, B and C) of thermal comfort demands which are described in TABLE III. They show that for good weather, as the nature resources can be fully used, the saved energy is evident. The most obvious energy saving using EETCC algorithm is category C about 46.28 %. But for bad weather, to maintain the room thermal comfort environment is mainly depending on the usage of air-conditioner, the influence of supervisory controller for energy efficiency is not much obvious. The most obvious energy saving in this case is category B about 27.32 %.

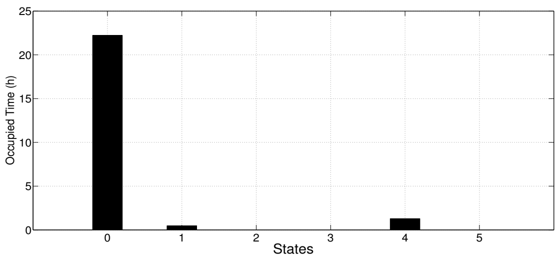

Fig. 7: Occupied time of the state in autumn

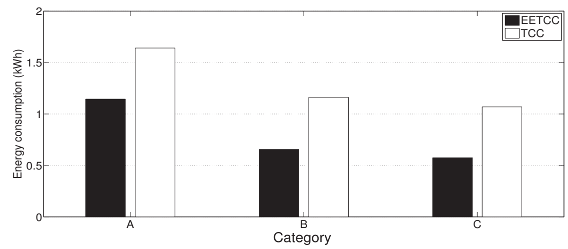

Fig. 9: Energy consumption in autumn

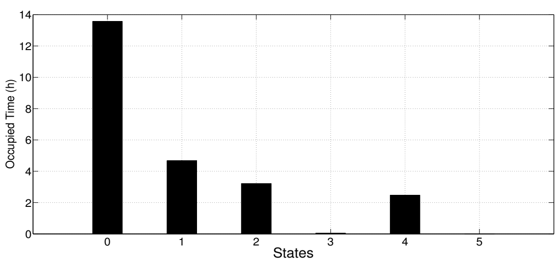

Fig. 8: Occupied time of the state in summer

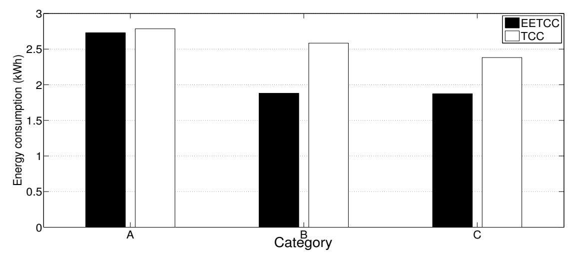

Fig. 10: Energy consumption in summer

V. Concluding Remarks

In this paper, we have presented the design and model of TCC system with three actuators: air-conditioner, window and curtain by using CPS approach. We have conducted simulations under two different weather conditions to evaluate and verify the proposed EETCC algorithm. By using natural resource to maintain the thermal comfort level of indoor home environment in comfort zone, our system can achieve the relative high energy efficiency. Simulation results reveal that our algorithm is adaptable and feasible for satisfying different needs of thermal comfort in the home environment.

For the future works, we will expand our proposed algorithm to the entire house building, use computational fluid dynamics (CFD) software to simulate the spatial distribution of PMV index. In order to more fully consider the needs of peoples' comfort and leverage the energy efficiency potential of control system, much more parameters (e.g., CO_2, lighting, etc.) will be included in our design. Furthermore, as a whole design, the capital expenditures for implementing building HVAC system should also be considered. A research for co-design of energy efficient control algorithm and system implementing monetary cost will be conducted. We will evaluate and testify our designed system by conducting a few simulations and experiments in our intelligent home environment, iHouse.

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