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Description	

Design and Evaluation of Hybrid Temperature Control for Cyber-Physical Home Systems

Abstract: The design of control system is crucial for improving the comfort level of home environment. Cyber-Physical Systems (CPSs) can offer numerous opportunities to design high efficient control systems. In this paper, we focus on the design and evaluation of temperature control systems. By using the idea of CPS, a hybrid temperature control (HTC) system is proposed. Through an energy efficient temperature control (EETC) algorithm, HTC system enables to maintain the room temperature in the desired interval. As the tight integration of physical and cyber worlds, sensing accuracy of physical platform has significant impact on the performance of HTC system. Through simulations and field experiments, the relationship between control performance and sensing accuracy is captured. A fitting function method is proposed to improve the sensing accuracy without increasing monetary cost of the system implementation. By using this method, the performance of HTC system can be increased obviously.

Keywords: Temperature Control; Hybrid Systems; Cyber-Physical Systems; Smart Home; Fitting Function.

1 Introduction

Technology advances allow us to design smart home systems to provide high comfortable living environment. At the same time, the performance requirements of control systems keep on increasing. To meet these demands, Cyber-Physical Systems (CPSs) can offer numerous opportunities. CPS in (Lee and Seshia, 2014; Derler, Lee and Vincentelli, 2012) is defined as a system which is tight integration of computation, communication, and control for active interaction between physical and cyber elements. In CPS, sensors and actuators are networked to sense, monitor, and control the physical world. In recent years, CPS has enlivened many critical fields for human life such as critical infrastructures, transportation, energy, and health (Parolini et al., 2012; Zhang et al., 2012; Jiang et al., 2012).

Some of them mainly for home environment are so called cyber-physical home systems. Many researches have contributed to these systems. For example, authors in (Lai et al., 2011) proposed a OSGi-based service architecture for cyber-physical home control systems, which supports service-oriented control methods. An extension of existing software architecture tool, called AcmeStudio, for the modeling and analysis of CPS at the architecture level is introduced in (Rajhans et al., 2009). Three entities are defined: the cyber domain, the physical domain, and their interconnection. An example of temperature control system is used to illustrate the architectural modeling. In (Wan et al., 2011), many application fields for CPS are introduced, which includes assisted living, home care, traffic control, safety, and automotive systems.

As for the modelling and control aspect, various strategies have been proposed. In (Radecki and Hencey, 2012), unscented Kalman filtering has been used for online estimation of building thermal parameter estimation. In (Maasoumy and Vincentelli, 2012), weather and occupancy prediction uncertainties are considered in the control design process, and a robust model predictive control mechanism against prediction uncertainties is studied. However, the uncertainties from the implemented platform measurements are not addressed. In (Abdennabi et al., 2014), a new strategy called multi-delay approach is proposed for the modelling and control of time-varying delay systems. In this new strategy, the time-varying delay systems are modeled by a multi-delay model representation, and the proposed controller guarantees a finite time convergence. The focus of these papers is on physical modeling and control design without taking into account the limitations of the implemented physical platform.

Unlike these works, in this research, we focus on the design of temperature control for cyber-physical home systems with consideration of the limitation of the implemented physical platform. By using the design idea of tight integration of cyber and physical actions, we present a hybrid temperature control (HTC) system which is a part of cyber-physical home systems. It combines supervisory and proportional-integral-derivative (PID) controllers. Through an energy efficient temperature control (EETC) algorithm, our proposed HTC system enables to monitor and maintain the room temperature in the desired interval with three actuators: air-conditioner, window and curtain. As the tight integration of physical and cyber worlds, the quality of the implementation physical platform has significant impact on the performance of HTC system. Many aspects (e.g., sensing accuracy, communication reliability) of the physical platform can influence the performance. In this paper, we focus on studying the relationship between sensing accuracy and the control performance.

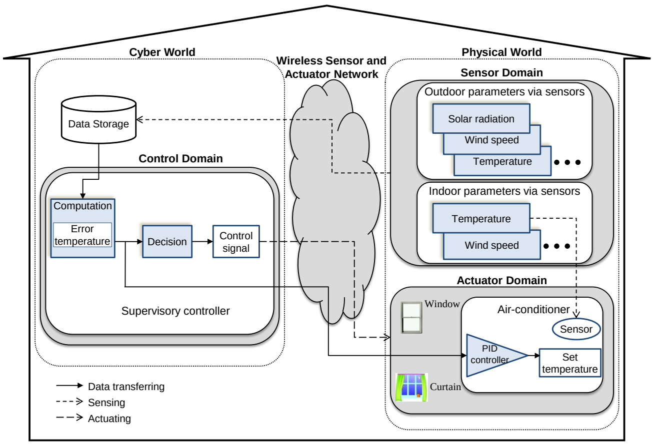

Figure 1 Hybrid temperature control (HTC) system

The main contributions of the paper are:

- Design the HTC system with three actuators by using the design idea of CPS.
- Study the important role of curtain in controlling room temperature.
- Conduct both simulations and field experiments to capture the relationship between control performance and sensing accuracy of the implementation physical platform.
- Propose a fitting function method to improve the sensing accuracy without increasing monetary cost of the system implementation. The proposed method can be adopted in a general design case of temperature control systems, and through this method, the performance of HTC system can be increased obviously.

The rest of the paper is organized as follows: The design and modeling of the HTC system, and the proposed EETC algorithm used in the supervisory controller are described in Section 2. The important role of curtain in controlling room temperature is also given in that section. In Section 3, the relationship between control performance and sensing accuracy is addressed. In Section 4, a fitting function method is proposed. Experiments and simulations are conducted to test and verify the proposed method. Some relevant conclusions and future works are drawn in Section 5.

2 Hybrid Temperature Control System

2.1 System Architecture

Figure 1 shows the basic architecture of HTC system. In this architecture, cyber world and physical world are defined. Wireless sensor and actuator network (WSAN) is used to connect these two worlds. The sensors in the physical side send the environment factors periodically to supervisory controller in the cyber side. Subsequently, the supervisory controller computes an error value which is a different value between current room temperature and the desired room temperature. Based on the error value, the supervisory controller figures out a control signal to trigger appropriate actuators (air-conditioner, window, and curtain) to adjust the room temperature. The operations of window and curtain are just opening and closing, but when air-conditioner is triggered, two steps are needed for controllers to generate a control input. First, supervisory controller sends the error value to the PID controller inside the air-conditioner. Then, based on this value, the PID controller generates a set temperature as a control input signal to operate air-conditioner. There are there tunable gains in the PID controller, the tuned values are important for the performance of the PID controller. Many notable tuning methods can be used to tune the three gains. For example, Ziegler-Nichols method and internal model control-PID (IMC-PID) tuning rules. Authors in (Elkhateeb and Badr, 2014) also gave a method by using inertia weight-based artificial bee colony method to tune the PID controller.

2.2 State Description

The HTC system is organized in six states, which are represented as numerical number 0 - 5, shown in Table 1. For the consideration of energy efficiency, states with turning on the air-conditioner while opening the window are not allowed.

2.3 Mathematical Representation

The room model proposed in (Shein et al., 2012) is applied in this paper. An equation of the dynamic change of room temperature is:

$$\frac{dT_r(t)}{dt} = \frac{1}{\beta} \sum Q(t) \tag{1}$$

where the $T_r(t)$ is the room temperature; t is the time instant; β is the product of air density, room volume, and air specific heat capacity; $Q(t)$ means heat gains of the room at time t. Five types of heat gains are considered: heat gain from air-conditioner (Q_{aircon}), heat convection from the open window ($Q_{convection}$), heat conduction due to temperature difference between inside and outside ($Q_{conduction}$), heat gain due to solar radiation through window ($Q_{radiation}$), and the heat gain from occupants ($Q_{occupant}$). Based on the different states as described in Table 1, the calculation for $\sum Q$ is as follows:

- state 0 and 1
  $\sum Q = Q_{conduction} + Q_{radiation} + Q_{occupant}$
- state 2 and 3
  $\sum Q = Q_{conduction} + Q_{radiation} + Q_{occupant} + Q_{convection}$
- state 4 and 5
  $\sum Q = Q_{conduction} + Q_{radiation} + Q_{occupant} + Q_{aircon}$

Table 1 States of HTC System (# means OFF/closed; ○ means ON/open)

Status	Air Conditioner	Window	Curtain
State 0	#	#	#
State 1	#	#	○
State 2	#	○	#
State 3	#	○	○
State 4	○	#	#
State 5	○	#	○

The equations used to calculated these heat gains and the validation of the room model with air-conditioner and window can be found in (Shein et al., 2012). The effect of curtain will be studied in section 2.5. Note that, if the value of $Q(t)$ is negative, it means the room is losing heat, and its temperature will decrease.

2.4 Supervisory Control

The supervisory controller decides which state system should transfer at each time instant. It outputs the control signals based on the proposed EETC algorithm summarized in Algorithm 1. The EETC algorithm is an improvement algorithm from the supervisory control algorithm described in (Shein et al., 2013), and refers to the algorithm described in research (Cheng et al., 2013). Performance evaluation of the original supervisory control algorithm can also be found in (Shein et al., 2013).

In HTC system, in order to use nature resources to reduce energy cost, supervisory controller prefers to choose states without using air-conditioner. At the time instant t, if room temperature $T_r(t)$ is in interval $[\mathtt{T}^{\mathtt{l}}_{\mathtt{th}}\ \mathtt{T}^{\mathtt{u}}_{\mathtt{th}}]$, supervisory controller chooses the state that leads to the minimum change of room temperature from the states without using air-conditioner, where $\mathtt{T}^{\mathtt{l}}_{\mathtt{th}}$ and $\mathtt{T}^{\mathtt{u}}_{\mathtt{th}}$ are the lower and upper threshold values of the desired room temperature respectively. If current room temperature is not in the interval of the desired temperature, system needs to transfer to state using air-conditioner. In Table 1, we can see that the conditions of window and curtain are the same in state 0 and 4. Similarly, state 1 and 5 also maintain the same conditions of the window and curtain. First, we should choose the state from state 0 and 1 to decide the conditions of window and curtain. Based on the sensed data of current room temperature, system can know current temperature is higher or lower than the desired value. By comparing the values of room heat gains under the two states, the proper one will be chosen. Then, the system should transfer to states using air-conditioner. If state 0 is chosen, the system transfers to state 4, otherwise to state 5. In addition, we have designed a *timer* to avoid frequent operation of actuators.

The other symbols used in the algorithm are: cs means output control signal decides to which state the system should transfer; s_c means system state at current time instant; $\mathtt{Time_{min}}$, time threshold, means the minimum time that the system has to stay in a state; Function $\mathtt{f}(se)$ outputs the total heat gain q_i for states i, $(i = 0, 1, 2, 3)$, where se is the sensed environment factors: wind speed, temperature, and solar radiation.

Algorithm 1 EETC

Input: sensed environment factors se, duration for the system that has stayed in current state *timer*
Output: control signal cs
if $timer < \mathtt{Time_{min}}$ **then**
  $cs := s_c$
else
  $q_i := \mathtt{f}(se)$, $i = 1, 2, 3, 4$
  if $\mathtt{T}^{\mathtt{l}}_{\mathtt{th}} \le T_r(t) \le \mathtt{T}^{\mathtt{u}}_{\mathtt{th}}$ **then**
    $S := \varnothing$
    for all $i, i = 1, 2, 3, 4$ **do**
      $v_i := |q_i|$
      $S := S \cup \{v_i\}$
    end for
    $id := \mathtt{min}(S)$, where $\mathtt{min}$ returns the index i of the minimum v_i in S
    $cs := s_{id}$
  else
    $S' := \varnothing$
    for all $i, i = 0, 1$ **do**
      $S' := S' \cup \{q_i\}$
    end for
    if $T_r(t) < \mathtt{T}^{\mathtt{l}}_{\mathtt{th}}$ **then**
      $id := \mathtt{max}(S')$, where $\mathtt{max}$ returns the index i of the maximum q_i in S'
    else
      $id := \mathtt{min}(S')$
    end if
    $cs := s_{id+4}$, where s_{id+4} is the proper state using air-conditioner
  end if
end if
return cs

2.5 Curtain

In the HTC system, there are three actuators: air-conditioner, window, and curtain. In this subsection, we will explain the important role of the curtain in HTC system which leads to the reduced usage of air-conditioner to improve the system energy efficiency. More details can be found in (Shein et al., 2013).

Curtain within the room can retain heat during winter and reject heat during summer. During the hot day of summer weather, before the sun shines directly onto the windows, the curtains should be closed. By this way, the heat from the sunshine is blocked before it enters which will help keep the room comfortable and lessen the usage of air-conditioner. During the cold day of winter weather, if the sunlight is strong, the curtain should be open. It allows the usage of natural sunlight during cold weather. In addition, the curtain can act like a shell to decrease the affection of heat conduction. Because of the facts explained above, the curtain is considered as one of the actuators in the HTC system. In the following, we will explain the equations for calculating the effect of curtain in affecting the room heat gain. There are two types of heat gains affected by curtain.

Table 2 Simulation parameters and settings

Parameter	Value
V_{room}: volume of room	5.0×4.1×2.4 (m^3)
c_{air}: specific heat capacity of air	1.012 $kJ/kg\cdot^\circ$ C
ρ_{air}: air density	1.2 kg/m^3
A_g: surface area of glass window	1.815 m^2
g_g: solar energy transmittance of window	0.79
ρ: solar reflectance of the curtain	0.5
τ: solar transmittance of curtain	0.2
G: thermal conductance of air	
between window and curtain	18 $W/m^2\cdot^\circ$ C
u_g: thermal transmittance of glass	3.4 $W/m^2\cdot^\circ$ C
R: thermal resistance of curtain	0.09 $m^2\cdot^\circ$ C/W
$Time^{on}_{min}$: time threshold	
for states using air-conditioner	5 min
$Time^{off}_{min}$: time threshold	
for states not using air-conditioner	3 min

Heat gain type 1: The heat gain when the sun shines through the window. It can be expressed in equation (Holmes, 2006):

$$Q_{radiation} = q_{rad} \cdot A_g \cdot g_t \tag{2}$$

where q_{rad} is solar radiation, A_g is surface area of glass window, g_t is total solar energy transmittance for system. When the curtain opens, g_t equals to g_g which is solar energy transmittance for glass, whereas when the curtain is closed, g_t means the solar energy transmittance of glass combined with curtain which can be calculated by the equation (British Standard, 2007):

$$g_t = g_g \cdot (1 - g_g \cdot \rho - \alpha \frac{u_g}{u_g + G}) \tag{3}$$

where ρ is solar reflectance of the side of the curtain facing the incident radiation, u_g is thermal transmittance of glass, G is thermal conductance of the air between window and curtain, and the value of α is calculated as:

$$\alpha = 1 - \tau - \rho \tag{4}$$

where τ is solar transmittance of the curtain.

Heat gain type 2: Heat gain through the glass window due to the temperature difference between outside and inside. It can be expressed as:

$$Q_{conduction} = u_t \cdot A_g \cdot (T_{out} - T_r) \tag{5}$$

where u_t is thermal transmittance for the system, A_g is surface area of glass window, T_{out} is outside temperature, and T_r is the room temperature. When the curtain opens, u_t equals to u_g which is thermal transmittance of glass, whereas curtain is closed, u_t means the thermal transmittance for window combined with curtain which can be calculated by following equation:

$$u_t = \frac{u_g}{1 + u_g \cdot \Delta R} \tag{6}$$

Figure 2 Experiment environment — iHouse

where ΔR is additional thermal resistance which can be calculated by the equation as follows:

$$\Delta R = 0.55R + 0.11 \tag{7}$$

where R is thermal resistance of curtain. Note that, the specific value used in the equation is depending on the air permeability of the curtain, and we choose the typical value from annex G in (European Standard EN ISO 10077-1, 2006) based on the field condition of our experimental environment.

2.5.1 Evaluation

To understand the role of curtain in HTC system, simulations are conducted in Simulink. The data used in the simulations are the raw data obtained from field experiments conducted in our smart home environment, iHouse. Figure 2 shows its overview. It has two floors with total area 107.76 m^2. More than 300 numbers of different kinds of sensors and home appliances are connected through home network. The environment data we used in the simulation is in autumn, the master room located in the second floor of iHouse is chosen as the observed room. The parameters and the setting values are shown in Table 2.

Figure 3 to 6 show the simulation results. Figure 3 shows the amount of heat gain from the solar radiation through the windows under the conditions of curtain open and closed. It shows that the amount of heat entering the room under curtain open state is much higher than closed condition. The maximum value is around noon time. By closing curtain, the amount of solar radiation can reduce about 937 W.

Figure 4 shows the results of heat conduction due to temperature difference between indoor room and outside environment. It shows that the difference of heat gain between curtain open and closed condition is relatively large when the inside and outside temperature difference is high. But when the temperature difference is small, the heat gain under two conditions is not obvious. By comparing the two different kinds of heat gain, we can see that the curtain affecting room heat gain mainly by affecting solar radiation rather than heat conduction.

The change of the cumulative room temperature is shown in Figure 5. We can see that the curtain can affect

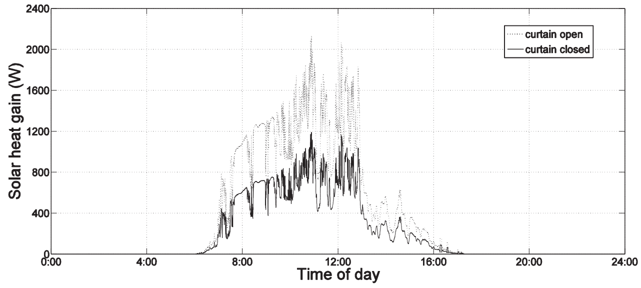

Figure 3 Heat gain from solar radiation

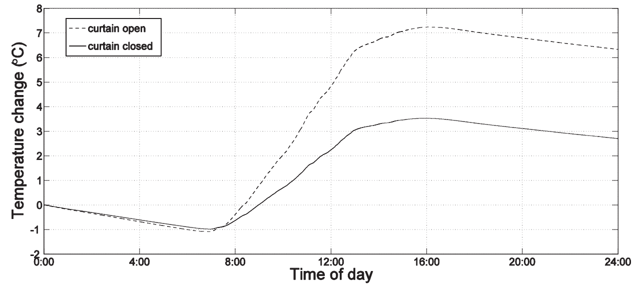

Figure 5 Cumulative room temperature change for one day

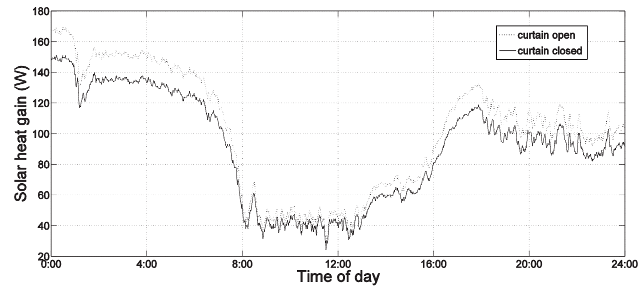

Figure 4 Heat gain from heat conduction

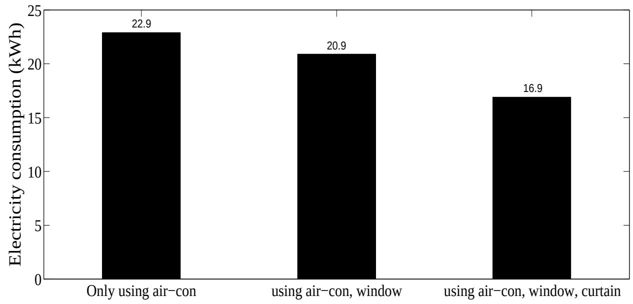

Figure 6 Energy consumption comparison

the room temperature obviously at day time (between 8:00 to 15:00) where the change of cumulative room temperature with curtain open is higher than curtain closed condition. At night time, the curtain does not affect room temperature because the solar radiation is very low.

Figure 6 shows the energy consumption of HTC system under different scenarios. The calculation of energy consumption is based on equation (9) which will be explained in the next section. It can be seen that when only air-conditioner is used to control the room temperature (keep window and curtain closed), the energy consumption is largest. When window and curtain are used, the energy consumption will become lower. We can see that, when curtain is used to control the room temperature, it can reduce the energy consumption to 80.86 % of not using curtain. This has demonstrated the effectiveness of curtain in controlling room temperature.

3 Control Performance & Sensing Accuracy

In this section, we study the relationship between the performance of HTC system and the sensing accuracy of the implemented physical platform.

3.1 Indices

3.1.1 Control Performance

1) Discomfort Index

The discomfort index I is defined as the sum of all the temperature violations during the course of system running (Maasoumy and Vincentelli, 2012).

$$I = \int_{\mathtt{t_s}}^{\mathtt{t_e}} [\mathtt{min}\{|T_r(t) - \mathtt{T^l_{th}}|, |T_r(t) - \mathtt{T^u_{th}}|\} \cdot \mathbf{1}_{\mathtt{L^c}} T_r(t)] dt \quad (8)$$

where $\mathtt{t_s}$, $\mathtt{t_e}$ are the start and ending time of the period of control system running respectively. $\mathtt{L} = [\mathtt{T^l_{th}}, \mathtt{T^u_{th}}]$ is the interval of desired room temperature. $T_r(t)$ is the room temperature at time t. $\mathbf{1}$ is the indicator function. Note that $\mathtt{L^c}$ refers to the absolute complementary set of $\mathtt{L}$ in the set of real numbers $\mathbb{R}$.

2) Energy Consumption

The energy consumption E is defined as:

$$E = \frac{1}{\mathtt{COP}} \int_{\mathtt{t_s}}^{\mathtt{t_e}} |Q_{aircon}(t)| dt \quad (9)$$

where $\mathtt{COP}$ is the coefficient of performance of air-conditioner. It is the ratio of heating or cooling provided by air-conditioner to its electrical energy consumption. 3.5 is applied in our simulation. $\mathtt{t_s}$, $\mathtt{t_e}$ are the start and ending time of the period of control system running. $T_r(t)$ is the room temperature at time t. $Q_{aircon}(t)$ is the cooling or heating load of air-conditioner at time t. It is calculated based on the equation:

$$Q_{aircon}(t) = \dot{m}(t)\mathtt{C_p}[T_{set}(t) - T_r(t)] \quad (10)$$

where $\dot{m}(t)$ is mass flow rate at time t, $\mathtt{C_p}$ is the specific heat capacity of air, $1.012kJ/kg \cdot ^\circ$ C is applied in our simulation. $T_{set}(t)$ is the set temperature of air-conditioner at time t.

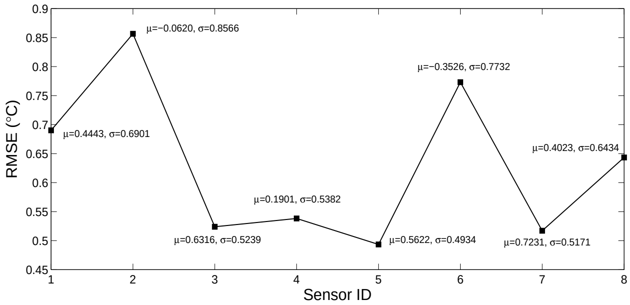

Figure 7 RMSE of sensed room temperature for eight sensors. Each data point is shown with μ (°C) and σ (°C).

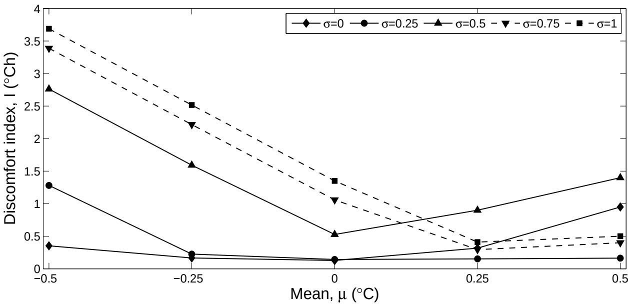

Figure 8 Discomfort index I under different combinations of μ (°C) and σ (°C).

3.1.2 Sensing Accuracy

The objective of the HTC system is to maintain the actual room temperature felt by occupants in the desired interval. As different spatial positions of the room with different temperature, in the system we use the readings of temperature sensors equipped in the room to estimate the actual room temperature felt by occupants. Sensing accuracy is used to evaluate the degree of the difference between the value of actual felt temperature and the sensed value. In order to get the actual room temperature felt by occupants, we put a temperature sensor at the position where occupants most frequently stay. Three indices are used to evaluate the sensing accuracy.

1) μ: the mean value of the probability density function of sensed error, where the sensed error is defined as the difference between sensed temperature value and the actual room temperature felt by occupants.

2) σ: the standard deviation of the probability density function of sensed error.

3) $RMSE$: root mean square error. It can be calculated as:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - x_i)^2} \tag{11}$$

where N is the number of the sensed data, y_i is the value of the i-th data obtained from the sensor located at the occupants' position, x_i is the value of the i-th data obtained from temperature sensor equipped in the room.

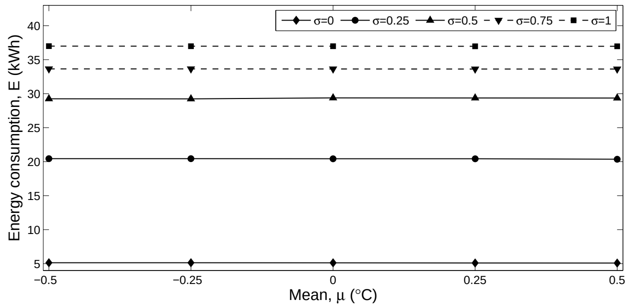

Figure 9 Energy consumption E under different combinations of μ (°C) and σ (°C).

3.2 Experiments

3.2.1 Setup

In order to study the relationship between control performance and the sensing accuracy, we conducted experiments for two weeks from December 9th to December 22nd, 2013. Our experiments were conducted in the master room of iHouse. Eight indoor temperature sensors are equipped on the corners (northeast, northwest, southeast, southwest) of the ceiling and floor, which spread out to cover the entire area of the master room. They are labeled with numerical IDs, from 1 to 8, based on the sequence of northeast, northwest, southeast, southwest. The first four IDs are for sensors equipped on the ceiling, and the remaining are for sensors on the floor. The position where occupants most stay is on a chair in front of a desk, which is at the center position of the room. We put a temperature sensor on the desk temporarily to get the actual room temperature felt by occupants. The interval for data recording of the temperature sensors is 2 minutes.

3.2.2 Results

Figure 7 depicts that only RMSE is not effective to indicate the accuracy of sensing system. It is because both μ and σ can have impact on the value of RMSE. As we can see that the sensor NO. 3 and NO. 4 have little difference on RMSE, which is only 2.62 % compared with the maximum RMSE variation of the experiment period, however the difference on μ is up to 41%. It is also can be known that sensors with large value of RMSE may have small value of μ or σ. For example, sensor NO. 2 has the largest value of RMSE among the eight sensors, but the value of μ is the smallest. It is necessary to use both μ and σ to denote sensing accuracy rather than just RMSE. In this way, we can have a relatively deep insight to explore the impact of different parameters (μ and σ) on the performance of control system.

3.3 Exploration of Control Performance and μ, σ

In order to study the relationship between control performance and μ, σ, sensed error with normal distribution based on μ and σ is added into our

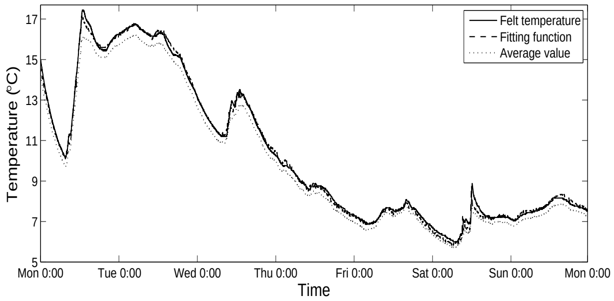

Figure 10 Room temperature for the week of training period (December 9–15, 2013). Note that *Felt temperature* represents the actual room temperature felt by occupants. The results of *Fitting function* and *Average value* is calculated based on the corresponding methods using the data from eight sensors equipped on the ceiling and floor.

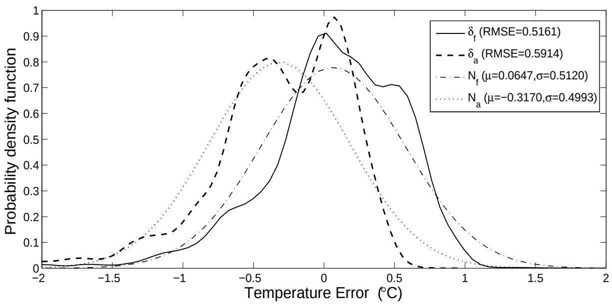

Figure 11 Probability density function of the sensed error for the week of training period (December 9–15, 2013). δ_f and δ_a represent the sensed error for using fitting function method and average method respectively. N_f and N_a represent the normal distribution with the same μ and σ as the δ_f and δ_a respectively.

simulator. Figure 8 and Figure 9 show the simulation results of running the control system for a whole day.

3.3.1 Discomfort Index

Figure 8 shows the results of discomfort index I under different combinations of μ and σ. We can see that, when $\mu = 0, \sigma = 0$, it means the system is perfectly accurate, the discomfort index I is the lowest. It also can be observed that the larger value of σ leads to the higher value of I under the condition of the same value of μ. Some exceptions happen when σ equals to or is larger than 0.75. For example, the value of I at data point ($\mu = 0.5$, $\sigma = 0.75$) is less than that at the data point ($\mu = 0.5$, $\sigma = 0$).

It also can be seen from the two lines for $\sigma = 0$ and $\sigma = 0.25$ that the lowest I value appears when $\mu = 0$. It is consistent with the intuitive idea that for a given value of σ, the smaller absolute value of μ gives more accurate sensed data which leads to better performance of I. However, as shown in the other three lines, $\sigma = 0.5, 0.75, 1$, this idea is no longer valid. This is because when the value of σ is up to a certain value, for our system is 0.75, which means the errors of sensed values spread out over a wide range, the data point at $\mu = 0$ will no longer gives the best performance of discomfort index. For example, when $\sigma = 0.75$, $\mu = 0.25$ rather than $\mu = 0$ can get the better performance.

3.3.2 Energy consumption

Figure 9 shows the results of system energy consumption E under different combinations of μ and σ. It depicts very clear that only σ can influence the system energy consumption while μ has no impact on it. The larger value of σ leads to the greater value of energy consumption.

The reason to get these results is that for a large value of σ, which means the errors of sensed values spread out over a wide range, in order to maintain the trajectory of room temperature in the desired interval, air-conditioner will be frequently operated, which leads to large amount of energy consumption. As to the parameter μ, which denotes the central tendency of sensed error, it will influence the degree of the deviation of control trajectory from the desired value. The influence is mainly reflected on discomfort index I.

4 Fitting Function Method

As analysis in Section 3, it is known that sensing accuracy is quite important for the overall performance of HTC system. To increase the sensing accuracy is crucial to improve the efficiency of the control system. The commonly used method for control system estimating the actual room temperature felt by occupants is using the average value of data sensed by the equipped sensors (e.g., Maasoumy et al., 2012). In this paper, in order to improve the sensing accuracy while avoid increasing system implementation monetary cost (e.g., adding more sensors), we try to propose a fitting function method which uses a fitting function to estimate the actual room temperature felt by occupants.

4.1 Establishment of Fitting Function

We have conducted two weeks experiments as described in Section 3. Data collected in the first week are used as training data to establish the fitting function, and the data collected in the second week are used as test data to validate the fitting function. Linear regression method is used to establish the fitting function. With the help of Simulink Design Optimization toolbox, the mean value of square error is minimized based on trust region reflective algorithm. The fitting function is formulated as follow:

$$T_r^f = 0.347T_1 + 0.0726T_2 + 0.398T_3 - 0.0446T_4 \\ -0.290T_5 + 0.385T_6 - 0.0300T_7 + 0.200T_8 \quad (12)$$

where T_r^f refers to the room temperature calculated by using fitting function, and T_i (i=1, 2 . . . 8) stands for the data obtained from the sensor with ID i.

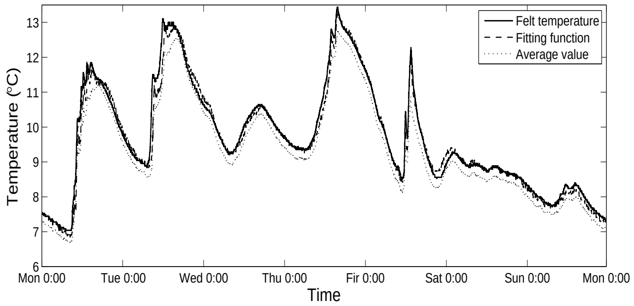

Figure 12 Room temperature for the week of validation period (December 16–22, 2013). Note that the symbols used in this figure are the same as in Figure 10.

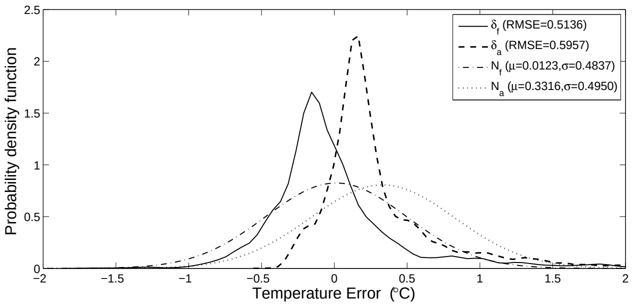

Figure 13 Probability density function of the sensed error for the week of validation period (December 16–22, 2013). Note that the symbols used in this figure are the same as in Figure 11.

Figure 10 shows the comparison results of estimated room temperature by using fitting function method and average value method. Figure 11 shows the probability density function of sensed error for using the two methods. In Figure 10, we can see that the results of both two methods have the same temperature change tendency in the actual room temperature felt by occupants. As shown in Figure 11, the results by using fitting function method are quite consistent with the actual room temperature felt by occupants. The mean value of the temperature error μ for fitting function method is 0.0647°C, lying within 1% of the maximum temperature variation (6.5°C) of the experiment period. Compared with fitting function method, the difference of the result of using average value method is mainly on μ. The value of μ for average value method is -0.3170°C, lying within 4.8% of the maximum temperature variation of the experiment period, which is much larger than using fitting function method. Meanwhile, the value of σ for average value method is 0.4993°C, which is almost the same as it for fitting function method (0.5120°C).

From above analysis, it can be known that using fitting function method can increase sensing accuracy of the control system mainly on μ rather than σ.

4.2 Validation of Fitting Function

The fitting function (12) is established by using the training data obtained from the first week of experiments. The data obtained from the second week is used as the test data to validate the function. By observing the performance of the fitting function with the test data, we can know whether it is valid.

The results are shown in Figure 12 and Figure 13. It can be seen from the figures that the results are pretty consistent compared with results shown in Figure 10 and Figure 11. It means that fitting function (12) is valid as the function reflects the temperature distribution of different spatial positions of the room.

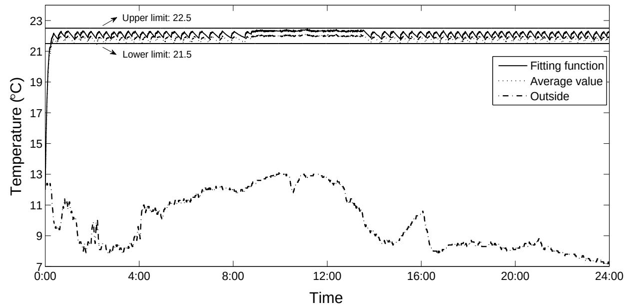

Figure 14 Control results of the actual room temperature felt by occupants. *Fitting function* and *Average value* represent corresponding methods used in simulation.

Table 3 Control Performance

Methods	μ (°C)	σ (°C)	I (°Ch)	E (kWh)
Fitting	0.01	0.47	0.52	26.96
Average	0.33	0.48	0.80	27.25

4.3 Performance

To evaluate the effect of the fitting function, we have conducted simulation by using different methods (fitting function method and average value method). The sensed data used in simulation is for December 20th, 2013. Figure 14 shows the control results, and Table 3 shows the value of indices.

The results in Figure 14 show that both methods can maintain the actual room temperature felt by occupants in the desired interval. The tendency of the control results for both methods is the same. In Table 3, we can see that the value of μ for average value method is much larger than fitting function method. This causes a downward deviation of the trajectory of the control results for average value method, which makes the discomfort index I greater than that using fitting function method. Compare the value of I for both two methods, the improvement by using fitting function method is 34%. As to energy consumption E, because the value of σ is almost the same under the two methods, the value of E is no much different. However, we still can say that the fitting method can improve the energy efficiency of the control system, as the performance of control system on each unit of energy consumption has been improved. These results are consistent with previous analysis.

5 Concluding Remarks

The design of control system is crucial for improving the comfort level of home environment. In this paper, we focus on the design of temperature control systems. By using the design idea of CPS, a HTC system was proposed. It enables to monitor and maintain the room temperature in the desired interval with three actuators: air-conditioner, window and curtain. The important role of curtain in controlling room temperature is also studied in this research. As the tight integration of physical and cyber worlds, the sensing accuracy of physical platform has significant impact on the performance of HTC system. Through simulations and field experiments, the relationship between control performance and sensing accuracy was captured. A fitting function method was proposed to improve the sensing accuracy without increasing monetary cost of system implementation. The proposed method can be adopted in a general design case of temperature control systems, and through this method, the performance of HTC system in terms of discomfort index can be increased obviously.

For the future works, we will extend our system to a whole building, some technologies for complex system will be introduced, e.g., decentralised control (Yan et al., 2014). Many aspect (e.g., communication reliability, computation delay) of the implementation platform will be considered and explored to study their impact on the performance of control systems. Another appealing direction is to dynamically change the fitting function based on keeping monitoring occupants' location.

References

Abdennabi, N, Ltaief, M, and Nouri, A.S. (2014) 'Discrete sliding mode control for time-varying delay systems: a multi-delay approach', *International Journal of Modelling, Identification and Control*, Vol. 22, No. 4, pp. 336–374.

British Standard (2007): *Solar protection devices combined with glazing Calculation of solar and light transmittance Part 1: Simplified method.* British Standard

Cheng, Z., Shein, W.W., Tan, Y., and Lim, A.O. (2013) 'Energy efficient thermal comfort control for cyber-physical home system', *IEEE International Conference on Smart Grid Communications*, Vancouver, Canada, pp. 797–802.

Derler, P., and Lee, E.A., and Vincentelli, A.S. (2012) 'Modeling Cyber-Physical Systems', *Proceedings of the IEEE*, Vol. 100, No. 1, pp.13–28.

Elkhateeb, N.A. and Badr, R.I. (2014) 'Dynamic inertia weight artificial bee colony versus GA and PSO for optimal tuning of PID controller', *International Journal of Modelling, Identification and Control*, Vol. 22, No. 4, pp. 307–317.

European Standard EN ISO 10077-1 (2006): *Thermal performance of windows, doors and shutters — Calculation of thermal transmittance — Part 1: General.* ISO.

Holmes, M. (2006) *Environmental design guide A*, CIBSE.

Jiang, Z., Pajic, M., and Mangharam, R. (2012) 'Cyberphysical modeling of implantable cardiac medical devices', *Proceedings of the IEEE*, Vol. 100, No. 1, pp. 122–137.

Lai, C.F., Ma, Y.W., Chang, S.Y., Chao, H.C., and Huang, Y.M. (2011) 'OSGi-based services architecture for cyber-physical home control systems', *Computer Communication*, Vol. 34, No. 2, pp. 184–191.

Lee, E.A. and Seshia, S.A. (2014) *Introduction to Embedded Systems, A Cyber-Physical Systems Approach*, 1.5 ed., [online] http://LeeSeshia.org.

Maasoumy, M., and Vincentelli, A.S. (2012) 'Optimal control of building HVAC systems in the presence of imperfect predictions', *ASME Dynamic System Control Conference*, Fort Lauderdale, USA, pp. 257–266.

Maasoumy, M., Zhu, Q., Li, C., Meggers, F., and Vincentelli, A.S. (2013) 'Co-design of control algorithm and embedded platform for building HVAC systems', *ACM/IEEE International Conference on Cyber-Physical Systems*, Philadelphia, USA, pp. 61–70.

Parolini, L., Sinopoli, B., Krogh, B.H., and Wang. Z. (2012) 'A cyberphysical systems approach to data center modeling and control for energy efficiency', *Proceedings of the IEEE*, Vol. 100, No. 1, pp. 254–268.

Radecki, P. and Hencey, B. (2012) 'Online building thermal parameter estimation via unscented kalman filtering', *American Control Conference*, Montreal, Canada, pp. 3056–3062.

Rajhans, A., Cheng, S.-W., Schmerl, B., Garlan, D., Krogh, B.H., Agbi, C., and Bhave, A., (2009) 'An architectural approach to the design and analysis of cyber-physical systems', *Electronic Communications of the EASST*, Vol. 21.

Shein, W.W., Tan, Y., and Lim, A.O. (2012) 'PID controller for temperature control with multiple actuators in cyber-physical home system', *International Conference on Network-Based Information Systems*, Melbourne, Australia, pp. 423–428.

Shein, W.W., Cheng, Z., Tan, Y., and Lim, A.O. (2013) 'Study of temperature control using cyber-physical system approach in home environment', *IEEE International Conference on Cyber-Physical Systems, Networks, and Applications*, Taipei, Taiwan, pp. 78–83.

Wan, J., Yan, H., Suo, H., and Li, F. (2011) 'Advances in cyber-physical systems research', *KSII Transactions on Internet and Information Systems*, Vol. 5, No. 11, pp. 1891–1908.

Yan, X.G., Zhang, Q., Spurgeon, S.K., Zhu, Q., and Fridman, M. (2014) 'Decentralised control for complex systems – an invited survey', *International Journal of Modelling, Identification and Control*, Vol. 22, No. 4, pp. 285–297.

Zhang, W., Kamgarpour, M., Sun, D., and Tomlin, C.J. (2012) 'A hierarchical flight planning framework for air traffic management', *Proceedings of the IEEE*, Vol. 100, No. 1, pp. 179–194.