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Description	

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Fitting Method for Hybrid Temperature Control in Smart Home Environment

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***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 of temperature control systems. By using the idea of CPS, a hybrid temperature control (HTC) system is proposed. It combines supervisory and proportional-integral-derivative (PID) controllers. Through an energy efficient temperature control (EETC) algorithm, 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 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*—fitting function, temperature control, hybrid systems, cyber-physical systems, smart home.**

I. 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 [**??**], [**??**] 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 [**??**], [**??**], [**??**].

Some researches on CPS, especially for home environment can be found in [**??**], [**??**], [**??**]. Authors in [**??**] 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 was introduced in [**??**]. Three entities were defined: the cyber domain, the physical domain, and their interconnection. An example of temperature control system was used to illustrate the architectural modeling. In [**??**], many application fields for CPS were introduced, which includes assisted living, traffic control, safety, and automotive systems.

Unlike these works, in this research, we focus on the design of temperature control systems for smart home environment. By using the design idea of CPS, we present a hybrid temperature control (HTC) system. 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. Here, the term "actuator" is defined as an object that commonly exists in home environment, and can potentially change the room temperature. 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.

The main contributions of this paper are: (*i*) to design the HTC system with three actuators by using the design idea of CPS, (*ii*) to conduct both simulations and field experiments to capture the relationship between control performance and sensing accuracy of the implementation physical platform, and (*iii*) to 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. 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 **??**. In Section **??**, the relationship between control performance and sensing accuracy is addressed. In Section **??**, 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 **??**.

II. Hybrid Temperature Control System

A. System Architecture

Fig. **??** 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

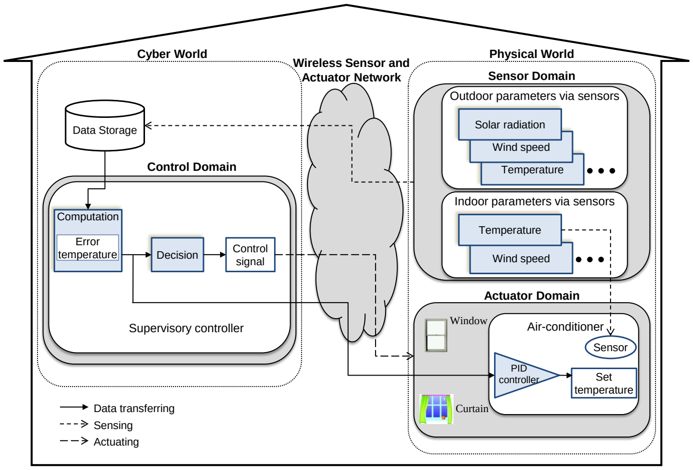

Fig. 1: Hybrid temperature control (HTC) system

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.

B. Mathematical Representation

The room model proposed in [**??**] 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 ($Q_{occupant}$). The equations used to calculated these heat gains and the validation of the room model can be found in [**??**], [**??**]. Note that, if the value of $Q(t)$ is negative, it means the room is losing heat, and its temperature will decrease.

C. State Description

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

TABLE I: States of HTC System

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

means OFF/closed; ○ means ON/open

D. Supervisory Control

The supervisory controller decides to which state system should transfer at each time instant. It outputs the control signals based on the proposed EETC algorithm summarized in Alg. **??**. The EETC algorithm is a improvement algorithm from the supervisory control algorithm described in [**??**], and refers to the algorithm described in our previous research [**??**]. Performance evaluation of the original supervisory control algorithm can also be found in [**??**].

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 **??**, 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. 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; $\mathtt{Time}_{\mathtt{min}}$ 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.

III. Control Performance & Sensing Accuracy

A. Indices

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 [**??**].

$$I = \int_{\mathtt{t_s}}^{\mathtt{t_e}} [\mathtt{min}\{|T_r(t) - \mathtt{T}^{\mathtt{l}}_{\mathtt{th}}|, |T_r(t) - \mathtt{T}^{\mathtt{u}}_{\mathtt{th}}|\} \cdot \mathbf{1}_{\mathtt{L}^c} T_r(t)]dt \tag{2}$$

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 $\mathtt{T^l_{th}} \leq T_r(t) \leq \mathtt{T^u_{th}}$ **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 $T_r(t) < \mathtt{T^l_{th}}$ **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

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:

$$E = \frac{1}{\mathtt{COP}} \int_{\mathtt{t_s}}^{\mathtt{t_e}} |Q_{aircon}(t)| dt \tag{3}$$

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:

$$Q_{aircon}(t) = \dot{m}(t)\mathtt{C_p}[T_{set}(t) - T_r(t)] \tag{4}$$

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

Fig. 2: Experiment environment — iHouse

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

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (y_i - x_i)^2} \tag{5}$$

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.

B. Experiments

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 iHouse which is a experimental smart home environment, located in Nomi city, Ishikawa prefecture, Japan. Fig. **??** 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 Echonet Lite which is a kind of home network.

The room used in experiments is the master room, located on the second floor. 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

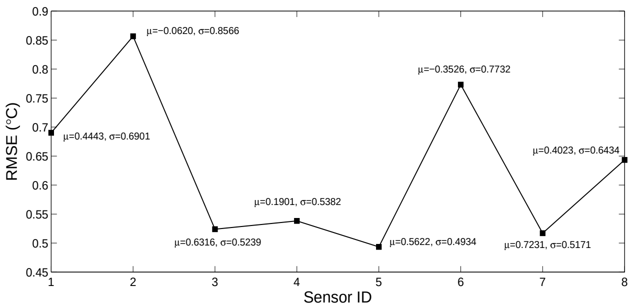

Fig. 3: RMSE of sensed room temperature for eight sensors. Each data point is shown with μ ($^{\circ}$C) and σ ($^{\circ}$C).

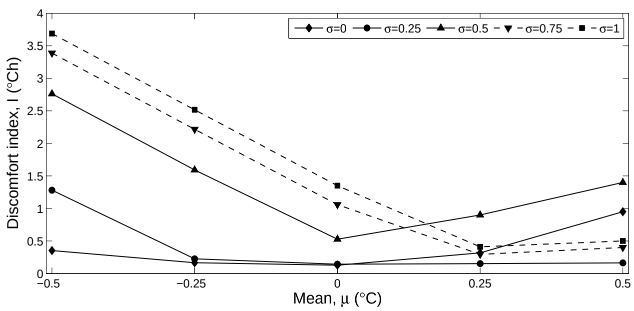

Fig. 4: Discomfort index I under different combinations of μ ($^{\circ}$C) and σ ($^{\circ}$C).

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.

2) Results: Fig. **??** 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.

C. 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 simulator. Fig. **??** and Fig. **??** show the simulation results of running the control system for a whole day.

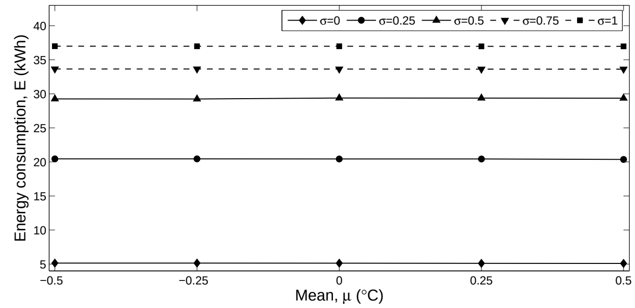

Fig. 5: Energy consumption E under different combinations of μ ($^{\circ}$C) and σ ($^{\circ}$C).

1) Discomfort Index: Fig. **??** 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.

2) Energy consumption: Fig. **??** 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.

IV. Fitting Function Method

As analysis in Section **??**, 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 [**??**]. In this paper, in order to

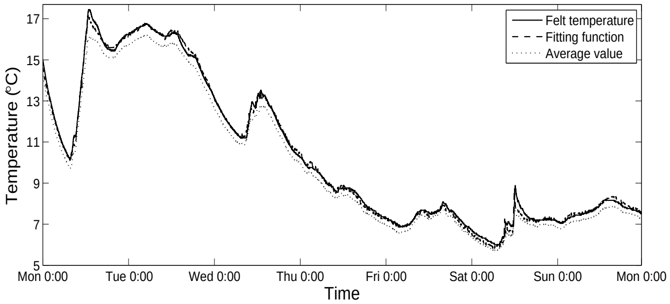

Fig. 6: Room temperature for the week of training period (December 9–15, 2013). Note that *Felt temperature* represents the actual room temperature felt by occupants. The results of *Fitting function* and *Average value* is calculated based on the corresponding methods using the data from eight sensors equipped on the ceiling and floor.

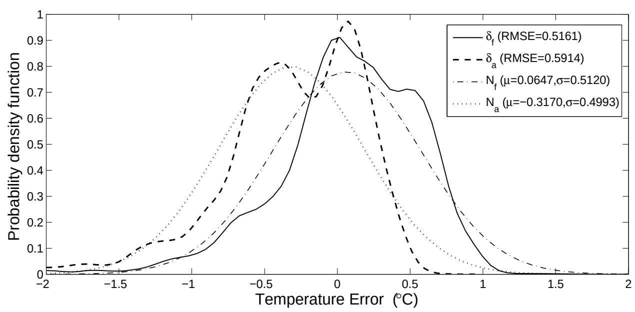

Fig. 7: Probability density function of the sensed error for the week of training period (December 9–15, 2013). δ_f and δ_a represent the sensed error for using fitting function method and average method respectively. N_f and N_a represent the normal distribution with the same μ and σ as the δ_f and δ_a respectively.

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.

A. Establishment of Fitting Function

We have conducted two weeks experiments as described in Section **??**. 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:

$$T_r^f = 0.347T_1 + 0.0726T_2 + 0.398T_3 - 0.0446T_4 \\ -0.290T_5 + 0.385T_6 - 0.0300T_7 + 0.200T_8 \quad (6)$$

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.

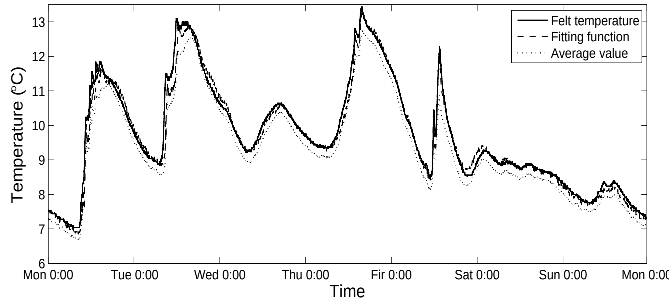

Fig. 8: Room temperature for the week of validation period (December 16–22, 2013). Note that the symbols used in this figure are the same as in Fig. **??**.

Fig. **??** shows the comparison results of estimated room temperature by using fitting function method and average value method. Fig. **??** shows the probability density function of sensed error for using the two methods. In Fig. **??**, we can see that the results of both two methods have the same temperature change tendency as the actual room temperature felt by occupants. As shown in Fig. **??**, 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 $0.0647°\mathrm{C}$, lying within 1% of the maximum temperature variation ($6.5°\mathrm{C}$) 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 -$0.3170°\mathrm{C}$, 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 $0.4993°\mathrm{C}$, which is almost the same as it for fitting function method ($0.5120°\mathrm{C}$).

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.

B. Validation of Fitting Function

The fitting function (**??**) 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 Fig. **??** and Fig. **??**. It can be seen from the figures that the results are pretty consistent compared with results shown in Fig. **??** and Fig. **??**. It means that fitting function (**??**) is valid to be used for other date as the function reflects the temperature distribution of different spatial positions of the room.

C. Simulation Results

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. Fig. **??** shows the control results, and Table **??** shows the value of indices.

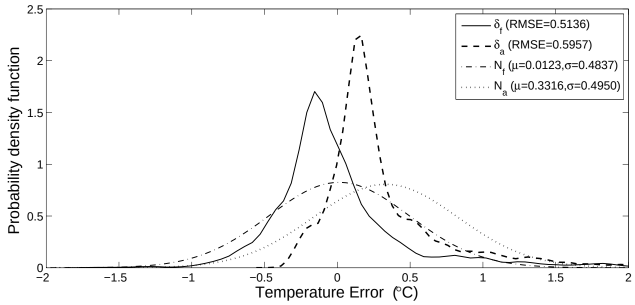

Fig. 9: Probability density function of the sensed error for the week of validation period (December 16–22, 2013). Note that the symbols used in this figure are the same as in Fig. **??**.

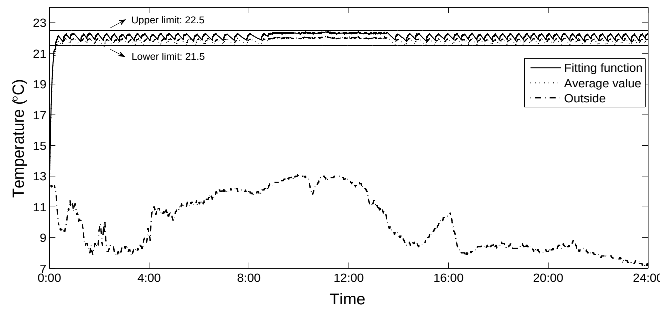

Fig. 10: Control results of the actual room temperature felt by occupants. *Fitting function* and *Average value* represent corresponding methods used in simulation.

The results in Fig. **??** 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 **??**, 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.

TABLE II: Control Performance

Methods	μ (°C)	σ (°C)	I (°Ch)	E (kWh)
Fitting Function	0.0123	0.4721	0.5278	26.96
Average Value	0.3300	0.4832	0.8000	27.25

V. 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 hybrid temperature control (HTC) system was proposed. It enables to monitor and maintain the room temperature in the desired interval. 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. Through this method, the performance of HTC system can be increased obviously. For the future works, some advanced strategies (e.g., machine learning) will be used in our system. We will consider other aspects (e.g., communication reliability, computation delay) of the implementation platform, and explore their impact on the performance of control systems. Another appealing direction is to dynamically change the fitting function based on keeping monitoring occupant's location.

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