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Description	

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Study of Temperature Control in Cyber-physical Home System Environment

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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 temperature control to build a thermal comfort controller for the existing hybrid temperature control (HTC) system, which is based on the cyber-physical system (CPS) approach. By using air-conditioner, window and curtain, our proposed controller can acquire the desired temperature under the high energy efficiency. Through the raw data from experiments, we use MATLAB/Simulink simulation to evaluate and verify our proposed controller in the cyber-physical home system environment.

Keyword cyber-physical system, temperature control, hybrid system, actuator, smart house

1. 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 and control aspects, equipment loads and minimum energy efficiency increase speedily. The improved heating, ventilation and air-conditioning system (HVAC) systems and control design strategies can offer numerous opportunities to meet those demands within efficient costs.

In this research, we present cyber-physical system (CPS) aspect the room temperature control system along with the supervisory controller and conventional Proportional and Integral (PI) controller. We correlate the room temperature with the multiple actuators. In this paper, actuator is defined as an object that can potentially change the environment temperature through the thermal heat at the home. Examples of actuators are air-conditioner, heater, window, curtain, etc. We design the CPS aspect hybrid temperature control (HTC) system which enables to monitor and maintain the desired temperature dynamically with the three actuators; air-conditioner, window and curtain.

The control of room temperature is a challenging task for the reasons of (i) changing the outside temperature in time that can be used as one of the thermal resources for controlling the room temperature; (ii) the time is very consuming to get the user's preference room temperature; and (iii) the dynamic of changing the environmental conditions. To challenge these points, CPS can be one of the potential approaches. CPS in [1], [2] is defined as a tight integration of computation, communication, and control for active interaction between physical and cyber (computational) 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 HTC system, we use the idea of designing 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 modelled HTC system, the room temperature is continuously sensed by the sensor and this sensed data is averaged and compared with the desired room temperature. Then, the supervisory controller decides the appropriate control input signal according to the feedback room temperature and the additional environment data (e.g. outside temperature, the heat entered through the window). Following these, the PI controller computes the control input to the physical system in case of the air-conditioner is triggered by the supervisory control. In HTC system, only the actuator air-conditioner is designed with PI controller.

This research aims to develop the practical application of CPS approach for temperature control system with multiple actuators in home environment. The contribution of this research is divided into two folds: (i) to present the room temperature control system with three actuators along with the supervisory control which is designed in an energy efficient way, (ii) to highlight the effect of the curtain in room temperature control. To understand how our proposed HTC system controls the room temperature in order to meet the user's preference while saving energy, we have developed a simulation in MATLAB/Simulink and showed with the simulation results.

The rest of this paper is structured as follows. Some state-of-the-art research works that are related to this paper are summarized in Section 2. In Section 3, we discuss the affect of the curtain in room temperature control and describe the mathematical formulation of the heat entered through the window glass and the curtain. In Section 4, we describe the design and modelling of the hybrid temperature control system and its mathematical representations. Also, the supervisory control and it's mode of operations, and PID controller are presented. Simulation scenario, setup, results and analysis are presented in Section 5. Some relevant conclusions and our future works are drawn in Section 6.

2. RELATED WORK

The following section reviews the existing researches on home automation system for controlling the temperature and the service platform of CPS applications in home environment.

Many researches and industrial works have been conducted in controlling the temperature of buildings and rooms with HVAC system. Such researches of intelligent control for the HVAC system can be found in [4], [5], [6] and [7]. For example, Witrant, et al [4] propose a model-based feedback control strategy for indoor temperature regulation in buildings equipped with underfloor air distribution. However, Homod, et al. [5] present a hybrid PID-cascade controller, which is a method for adaptively adjusting the PID gains using cascade feed forward for central air-conditioning system. Wang, et al. [6] propose a hybrid CMAC-PID control system for HVAC system, which combines the CMAC (Cerebellar model articulation controller) neural network and general PID control. A model-based design of embedded controllers for integrated building system to regulate the indoor room temperature is presented in [7].

Other relevant researches of CPS application for home environment system can be found in [8], [9], [10], [11], and [12]. Wang [8] 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. Lai, et al. [9] propose the OSGi-based service architecture for cyber-physical home control system, which supports service-oriented control methods. Their system uses the signals and the events in a virtual context for both controlling of home appliance and detecting of appliance position. Duchon, et al. [10] introduce an extension of existing software architecture too, called Acme Studio, for the modeling and analysis of cyber-physical system 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 tow zones (rooms). The CPS applications in [13] include medical devices and systems, assisted living, traffic control and safety, advanced automotive systems, energy conservation, and smart structure.

In particular, there is only limited work in the CPS approach for the temperature control with multiple actuators in home environment. In fact, this paper is closely related to our previous work [14]. In [14], we presented CPS approach room temperature control system with two actuators; air-conditioner and window. Apart from the existing research, this paper extends the work presented in [14] by adding one more actuator — the curtain. Moreover, there are few examples that studied the influent of the curtain in room temperature controlling. In this respect, the present study illustrates the influent of the opening/closing the curtain in room temperature control. The advantage of our proposed HTC system over a common home temperature control system is that the system is designed with interoperability among the three actuators along with the compromise between the user's preference and the energy cost.

3. TEMPERATURE CONTROL WITH CURTAIN

In this section, we explain the important role of the curtain to maintain the room temperature and to reduce the usage of air-conditioner/heater as well. The curtain within the room maintains a temperature closer to the room temperature, while the curtain closet to the window absorbs the heat or cold.

Since the energy efficient curtains retain heat during the winter and reject heat in the summer, resulting in lower cooling and heating loads. We can control how much sun is allowed to enter the home, and when, by adjusting the energy efficiency curtains to be either open or closed.

During the heat day of summer weather, before the sun shines directly onto the windows, the curtains are closed. By this way, the heat from the sun is blocked before it enters and warms the air will help keep the room comfortable and lessen the need for air-conditioning. During the day of cold weather if the window is receiving sunlight, the energy efficient curtain is opened. So, allowing the use of natural sunlight during cold weather will lessen the need to run the heater. Also, the curtains are closed as soon as the sun has set to keep all the heat from escaping through the window. Because of the facts as explained above, the curtain is considered as one of the actuators in our HTC system.

In the following, we explain the formulation of two types of heat entered through the glass window.

Type 1: The heat gain when the sun shines through the window can be expressed as explained in [15]

$$Q_{ss} = q_{rad} \cdot A_g \cdot g_t \tag{1}$$

where q_{rad} is solar radiation, A_g is surface area of glass window; g_t is total solar energy transmittance for system combined with curtain and window. When the curtain is opened, g_t=g_g which is total solar energy transmittance for glass.

When the curtain is closed, g_t can be calculated by the equation [16]

$$g_t = g_g \cdot (1 - g_g \cdot \rho - \alpha \cdot \frac{u}{u+G}) \tag{2}$$

where G is thermal conductance of the air between glass and curtain, is solar reflectance of the side of the curtain facing the incident radiation, and the value of α (3).

$$\alpha = 1 - \tau - \rho \tag{3}$$

where τ is solar transmittance of the curtain, u is thermal transmittance of glass.

Type 2: Heat gain through the glass window due to temperature difference between outside and inside and another gain due to solar radiation through windows. Heat gain through the glass due to the temperature difference between outside and inside can be expressed as

$$Q_{dth} = A_g \cdot u_t \cdot (T_{out} - T_r) \tag{4}$$

where A_g is surface area of glass window, u_t is thermal transmittance for the system that combined with the curtain and the window. When curtain opens, u_t=u_g which is thermal transmittance for window. When curtain is closed, u_t is calculated by following equation

$$u_t = \frac{u_g}{1 + u_g \cdot \Delta R} \tag{5}$$

where ΔR is additional thermal resistance which can be calculated by equation (7) as follows

$$\Delta R = 0.55R + 0.11 \tag{6}$$

where R is thermal resistance for curtain. The details of affect of curtain in room temperature control will be presented in Section 5 with the simulation results.

4. HYBRID TEMPERATURE CONTROL SYSTEM

In this section, we explain the detail of HTC system. First, we explain the design and modeling of HTC system and its mathematical representations. Following these, the supervisory control, it's mode of operations and PID controller are described.

4.1 HTC System Architecture

The feedback control of HTC system comprised of supervisory control and PI controller is showed in Figure 1. In our HTC system, the desired room temperature is maintained and controlled by three actuators; the air-conditioner, the window and the curtain cooperatively regardless of dynamic environment changes. The room temperature is periodically sensed by the sensors and these sensed data are sent to the supervisory control and PI controller.

Then, the supervisory control computes the control input signal according to the feedback room temperature and the additional environment data (e.g. the outside temperature, the heat entered through the window) and then decides which actuator should be active. Following these, in case of the air-conditioner is triggered by the supervisory control; the PI controller computes the control input to it. The pseudo code for supervisory control is shown in Fig. 2.

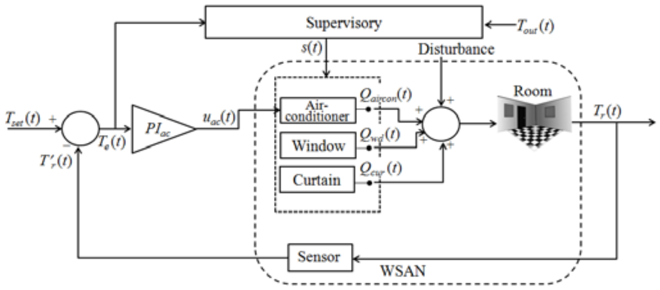


Fig. 1: Block diagram of HTC system.

Table 1. Symbols and definition.

Symbols	Definition
$s(t)$	system state at moment t
$T_r(t)$ (℃)	room temperature at moment t
T_{set} (℃)	desired room temperature
T_{off_sum} (℃)	offset temperature for typical summer weather
T_{off_win} (℃)	offset temperature for typical winter weather
Q_{sum} (W)	threshold value for room heat gain in typical summer weather
T_{sa}	setting temperature of air-conditioner
$Q(i)$	total heat gain under the state i
T_{so}	supplied outside temperature
N	number of occupants
Q_{win} (W)	threshold value for room heat gain in typical winter weather
$c(t)$	switch signal to decide next state
$timer_{nac}$ (s)	state holding time when air-conditioner is not used
$timer_{ac}$ (s)	state holding time when air-conditioner is used

4.2 Mathematical Representation

The mathematical representation of HTC system as explained in [14] are used in this paper. Here, we consider five types of heat that makes the changes of room temperature; heat gain from the air-conditioner (Q_{aircon}), heat gain from opening the window ($Q_{airflow}$), heat gain due to temperature difference between inside and outside through window only (Q_{dth}), heat gain due to solar radiation (sun shines) through window only (Q_{rad}), and the sensible heat gain and latent heat gain by occupants ($Q_{occupant}$).

Heat gain through the glass window is divided into two parts since there is a heat gain due to temperature difference between outside and inside (Q_{dth}) and another gain due to solar radiation through windows(Q_{ss}). The formulation of these two heat gain are described in detail in Section 3.

Algorithm supervisory control

```
for each $s(t) \in S$ do
    if $s(t) \in S_1 = \{s_0, s_1, s_2, s_3\}$ then
        $timer_{sh} = timer_{nac}$
    else
        $timer_{sh} = timer_{ac}$
    end if
    if ($timer < timer_{sh}$) then
        $c(t) \leftarrow s(t)$
    else
        if ($T_r(t) > T_{set} + T_{off\ sum}$) then
            $i \leftarrow \mathrm{argmin}_{i \in \{0,1,2,3\}} \{Q(i)\}$
            $q \leftarrow \min_{i \in \{0,1,2,3\}} \{Q(i)\}$
            if ($q \le Q_{sum}$) then
                $c(t) \leftarrow i$
            else
                $i \leftarrow \mathrm{argmin}_{i \in \{0,1\}} \{Q(i)\}$
                $c(t) \leftarrow i+4$
            end if
        elseif ($T_r(t) < T_{set} - T_{off\ win}$) then
            $i \leftarrow \mathrm{argmax}_{i \in \{0,1,2,3\}} \{Q(i)\}$
            $q \leftarrow \max_{i \in \{0,1,2,3\}} \{Q(i)\}$
            if ($q \ge Qwin$) then
                $c(t) \leftarrow i$
            else
                $i \leftarrow \mathrm{argmin}_{i \in \{0,1\}} \{Q(i)\}$
                $c(t) \leftarrow i+4$
            end if
        end if
    end if
end for
```

Fig. 2: Pseudo code for supervisory control.

4.3 Supervisory Control

A supervisory control represents a certain class of hybrid control systems. A supervisor decides which of the actuators that should be active at each time instant. The switching signals are determined by the supervisor based on proposed control algorithm in Fig. 2. Here, the continuous inputs to the supervisory are the error temperature computed from the feedback room temperature and the outside temperature, and the control signal is the continuous output.

The HTC system is organized in a set of six states: $S_{aoff,wcl,ccl}$, $S_{aoff,wcl,cop}$, $S_{aoff,wop,ccl}$, $S_{aoff,wop,cop}$, $S_{aon,wcl,ccl}$, $S_{aon,wcl,cop}$ which is defined as numerical number 0-5 respectively. In the following we explained the operation of each mode.

State 0 ($S_{aoff,wcl,ccl}$) : Air-conditioner is off, window is closed and curtain is closed.

State 1 ($S_{aoff,wcl,cop}$): Air-conditioner is off, window is closed and curtain open.

State 2 ($S_{aoff,wop,ccl}$): Air-conditioner is off, window open and curtain is closed.

State 3 ($S_{aoff,wop,cop}$): Air-conditioner is off and window and curtain open.

State 4 ($S_{aon,wcl,ccl}$) : Air-conditioner is on and window and curtain are closed.

State 5 ($S_{aon,wcl,cop}$) : Air-conditioner is on and window is closed and curtain open.

In the refinements of each state, the following differential equations govern the changes of the room temperature.

When the system is in $S_{aoff,wcl,ccl}$ and $S_{aoff,wcl,cop}$ states, the room temperature changes according to following equation below:

$$\frac{dT_r}{dt} = \frac{1}{\beta}(Q_{dth} + Q_{ss} + Q_{occupant}) \qquad (7)$$

When the system is in $S_{aoff,wop,ccl}$, $S_{aoff,wop,cop}$ states, the room temperature changes according to following equation below

$$\frac{dT_r}{dt} = \frac{1}{\beta}(Q_{dth} + Q_{ss} + Q_{occupant} + Q_{airflow}) \qquad (8)$$

When the system is in $S_{aon,wcl,ccl}$ and $S_{aon,wcl,cop}$ states, the room temperature changes according to following equation below

$$\frac{dT_r}{dt} = \frac{1}{\beta}(Q_{dth} + Q_{ss} + Q_{occupant} + Q_{aircon}) \qquad (9)$$

Q_{dth} and Q_{ss} values are calculated under the condition of curtain open or close according to the corresponding state as explained in Section 3.

4.4 PID Controller

PID controller consists of proportional, integral and derivative elements, is widely used in feedback control processes. Most of the controllers commissioned in HVAC systems use the PID type to control the environmental variables such as pressure, temperature, humidity, etc. This is mainly because PID is simple yet for most HVAC applications. In this research, our focus is to control the room temperature dynamically. Since fuzzy logic controller does not have integral part, in which it leads to the existence of steady-state error. Whereas, PID controller have a perfect effect in small- scale and regulate near the balance setpoint, where its integral action can finally cancel the error. The standard PID controller is described as

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de}{dt} \qquad (10)$$

where u is the control signal, K_p is proportional gain, K_i is integral gain, K_d is derivative gain and e is the control error. In our HTC system, only the actuator air-conditioner is designed with PI controller. We consider that the air-conditioner using a conventional PI controller varies the speed of the compressor motor, and controls the refrigeration load. Using MATLAB/Simulink toolbox, the parameters obtained is tested and the closest parameters to the practical value are used. The sampling period is 10 second.

5. SIMULATION STUDIES

5.1 Simulation Environment and Setup

In this section, we verify and examine how HTC system will behave in real physical world by making the simulation conducted in MATLAB/Simulink tool. In the simulation, we use the raw data from the experiments that were conducted at the smart house environment, iHouse, which is located at Nomi city, Ishikawa prefecture, Japan. The measured outside temperature of iHouse and the entered total heat from the sun through the windows of the bedroom on the second floor during the typical summer and winter weather are used in our simulation. This work was accomplished by the aid of home simulator presented in [17]. The windows and curtains are mounted with automatic opened/closed motor. In the bedroom, one air-conditioner of Mitsubishi type is also available. The other parameters and values used in the simulation are shown in Table 2. Moreover, we also consider the state settling time for regulating the amount of state transition. As a result, we can reduce the frequency of actuators operation.

Table 2. Simulation parameters and settings.

Parameter	**Value**
V_{room} (L×W×H) : room volume	$5.005m \times 4.095m \times 2.4m$
ρ_{air} : air density	1.2 kg/m^3
T_{set} : desired room temperature	25 ℃
T_{off_sum} : offset value in summer	0.2 ℃
T_{off_win} : offset value in winter	0.2 ℃
Ag_1 for type 1:	1.815 m^2
Ag_2 for type 2 :	0.66 m^2
A_{op1} for type 1 : surface area of window opening	1.815 m^2
A_{op2} for type 2 : surface area of window opening	0.66 m^2
u_{g1} for type 1	3.4 W/m^2℃
u_{g2} for type 2	1.7 W/m^2℃
g_{g1} for type 1	0.79
g_{g2} for type 2	0.41
τ	0.2
G	18 W/m^2℃
ρ	0.5
R	0.09 m^2℃$/W$
C_{air} : specific heat capacity air	1012 J/kg℃
CFM : cubic feet per minute	300 ft^3/min
v_{air} air velocity leaving the opening	3.4 m/s
c_d : effectiveness of air	0.61
SHG : sensible heat gain by occupants	230 Btu/h
LGH : latent heat gain by occupants	190 Btu/h
CLF : cooling load factor for the occupants	1
K_p for state 4($S_{aon,wcl,ccl}$) summer	11.5259
K_i for state 4($S_{aon,wcl,ccl}$) summer	0.07830
K_p for state5($S_{aon,wcl,cop}$) summer	7.6920
K_i for state5($S_{aon,wcl,cop}$) summer	0.05594
K_p for state 4($S_{aon,wcl,ccl}$) winter	11.5259
K_i for state 4($S_{aon,wcl,ccl}$) winter	0.07830
K_p for state 5($S_{aon,wcl,cop}$) winter	7.6920
K_i for state 5($S_{aon,wcl,cop}$) winter	0.0559
Q_{sum}	50 W
Q_{win}	60 W
$timer_{ac}$ (summer)	100s
$timer_{nac}$ (summer)	80s
$timer_{ac}$ (winter)	50s
$timer_{nac}$ (winter)	40s
COP	3.5

5.2 Simulation Results

To evaluate our new HTC system, in the first part, we conduct the simulations with two parts. In the first part, we focus on the study of the affect of curtain in room temperature and investigate how the usage of curtain can maintain the room temperature and reduce the usage of air-conditioner in winter only. In the second part, we add the curtain as an actuator in the HTC system, and study how the room temperature is controlled. The simulations are conducted for both winter and summer seasons.

5.2.1 Effect of Curtain on Heat Gain

Figures 3 to 5 show the simulation results of the study of the effect of curtain on the room temperature changes. Fig. 3 shows the simulation results of amount of heat gain from the solar radiation through the windows under conditions of curtain open and curtain closed. We observe that the amount of heat entering the room under curtain open state is much higher than close state. We can see the maximum value is around noon time. By closing curtain the amount of solar radiation is reduced about 937W.

Figure 4 shows the simulation results of heat gain from temperature difference between inside and outside. We observe that the difference between curtain open and curtain closed conditions is relative big when the temperature difference is huge. But when the temperature difference is small, the heat gain under two conditions is not obvious.

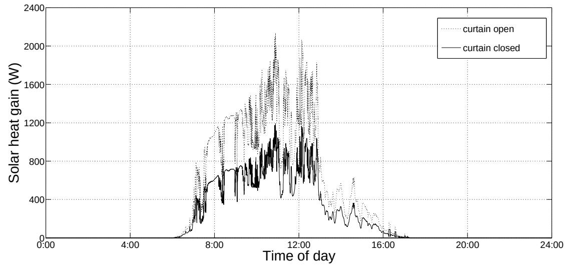


Fig. 3: Heat gain from solar radiation.

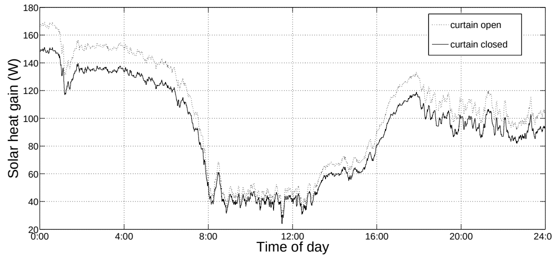


Fig. 4: Heat gain from heat conduction (temperature difference).

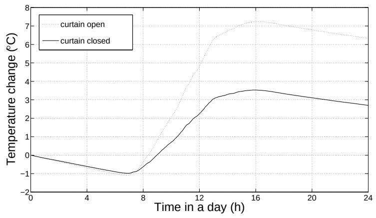
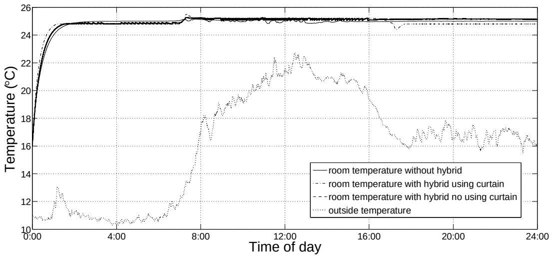
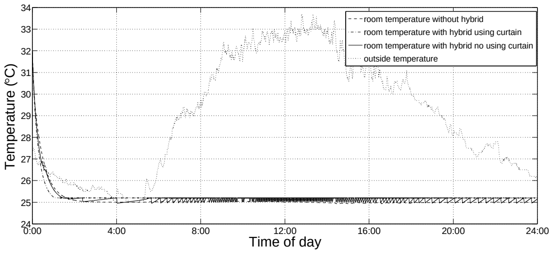


Fig. 5: Cumulative room temperature change for one day.

The change of the cumulative room temperature is shown in Fig. 5. We can see that the curtain can affect the room temperature obviously for one day. At night time, the curtain does not affect room temperature because the solar radiation is very low. However, we can see that the cumulative room temperature difference between curtain open and closed conditions at daytime is very high.

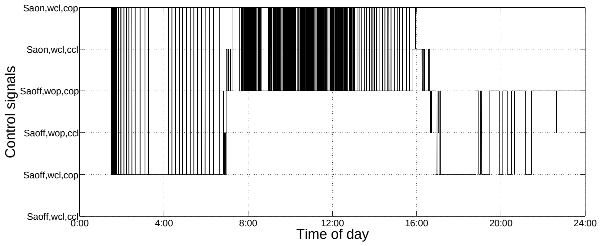


(a) Winter

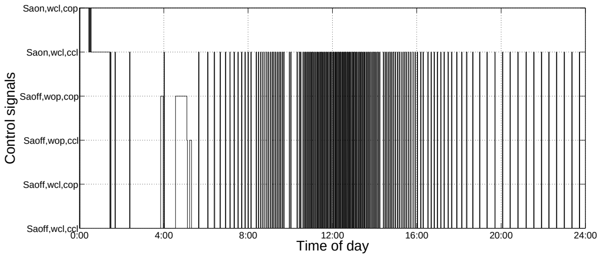


(b) Summer

Fig. 6: Room temperature change with/without supervisory control.

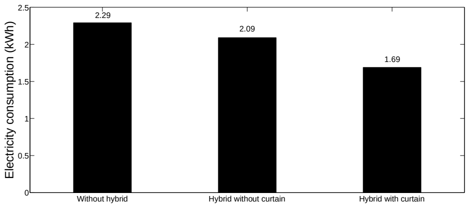


(a) Winter

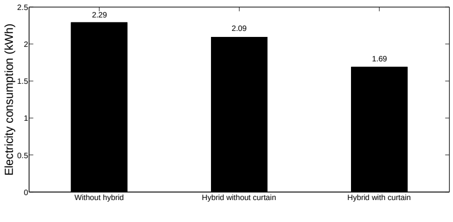


(b) Summer

Fig. 7: States statues of actuators.



(a) Winter



(b) Summer

Fig. 8: Energy consumption comparison.

From these simulation results, we understand that the curtain maintains the room temperature by blocking the heat from the sun in the heating day.

5.2.2 HTC Temperature Control for Winter and Summer

In this section, we present the simulation results both in summer and winter seasons. Figures 6-8 show the change of room temperature, the state statues of HTC system and the comparison of power consumption in winter and summer season respectively.

In Fig. 6, we can see that the variance of controlled room temperature among the three different conditions of supervisory control is small. Meanwhile, the room temperature is maintained within our defined upper and lower temperature levels.

Figure 7 shows the change of the state status of actuators. In order to reduce the frequent operation of the actuators, we define the settling time for each state. For the state using air-conditioner, its settling time is longer than without using it. This can prevent from the tiredness of the air-conditioner while maintaining the desired room temperature.

Figure 8 shows the energy consumption of air-conditioner for different scenarios. We can observe that the power consumption of air-conditioner without hybrid is largest among the three scenarios and hybrid control with curtain gives lower power consumption than without curtain.

6. CONCLUDING REMARKS

In this paper, we presented the design and model of HTC system with three actuators; air-conditioner, window, and curtain. The proposed HTC system model is composed with supervisory control and PI controller. Beside that we have studied the effect of the curtain in room temperature and we also defined the settling time for each state. This can prevent from the high number of ON/OFF frequents for the air-conditioner while the system is maintaining the desired room temperature. As a result, we can reduce the usage of air-conditioner to accomplish a better energy consumption. To the best of our knowledge, our proposed HTC system can attempt to operate in real-time to control the room temperature in home environment.

For the future works, we will study and design thermal comfort controller by considering other two parameters: relative humidity and wind speed. Then evaluate and testify the proposed system by simulations and experiments in iHouse.

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