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PID Controller for Temperature Control with Multiple Actuators in Cyber-Physical Home System

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Abstract: Nowadays, the need of room temperature control at home is significantly demanded. In this research, we present and model the hybrid temperature control (HTC) system, which is applied to monitor the desired temperature of a room at all times with an optimum resource cost. In our HTC system, we focus on controlling two actuators (i.e., air-conditioner and window) using a supervisory controller and a PI (Proportional-Integral) controller. The aims of this research are to develop a practical application of cyber-physical system approach for the HTC system and to investigate the influence of PI controller and supervisory controller on monitoring the desired room temperature. Through computer simulation, we verify and discuss the simulation studies of the HTC system.

Keywords: cyber-physical system, hybrid temperature control, supervisory controller, PID controller.

1. Introduction

Since the essential for comfort control at home is widely recognized nowadays, the smart control of thermal environments is needed from the standpoint of comfort, healthcare reasons and satisfaction. The comfort satisfaction can be improved by dynamically monitoring the parameters such as temperature, humidity, light, and presence at home. In this research, we are intended to focus on controlling the temperature parameter only. 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 actuator are air-conditioner, heater, window, door, etc. As a preliminary work, we are considered only two actuators, i.e., air-conditioner and window. We design a hybrid temperature control (HTC) system by applying the supervisory controller and PID controller. Since the derivative (D) element of PID controller will not be applied in this research, we specifically use the PI controller to describe the usage of both proportional (P) and integral (I) elements in this paper. In addition, our HTC system uses cyber-physical system (CPS) approach with the aim of timely control the multiple actuators to maintain the desired room temperature with the optimized cost.

The control of room temperature is a challenging task for the reasons of (1) changing the outside temperature in time that can be used as one of the thermal resources for controlling room temperature; (2) the time is very consuming to get the user's preference room temperature; and (3) the dynamic of changing the environmental conditions. To challenge these points, a CPS can be one of the potential approaches. CPS is defined as a tight integration of computation, communication and control for active interaction between physical and cyber (computational) elements [1]. In other words, CPS tends to feature a tight coupling between physical and software components and may be required to operate for long periods without human intervention. On the same hand, CPS in [2] is defined as an integration of computation, networking and physical dynamics, in which embedded devices such as sensors and actuators are wirelessly networked to sense, monitor and control the physical world. Furthermore, the idea of feedback cyber-physical control architecture is to exploit the measurements of the system's output to determine the control commands that yield the desired system behavior [3]. The sensors used to sense the operation of physical system, and send the collected data to the corresponding controller. The controller compares it against the desired value, compute the control commands, and send them to the actuators. The actuators perform actions onto the system to effect the desired change. This concept of feedback cyber-physical control system over the wireless sensor and actuator network (WSAN) is applied to our proposed HTC system for controlling desired temperature timely. Thus, we use the CPS approach to model the HTC system that consists of the supervisory controller and PI controller with the CPS characteristics that explained in [2], [4], [5], [6] and [7]. In our modeled HTC system, an instantaneous room temperature is always sensed by the sensor and this sensed data is averaged and compared with the desired room temperature. In HTC system, the supervisory controller decides the input control signal and the PI controller computes the control input to trigger the physical system (i.e., room temperature) according to the feedback room temperature. The goals of this research are to develop a practical application of CPS approach for the HTC system and to investigate the influence of PI controller and supervisory controller on monitoring the desired room temperature. In this research, our research contribution is divided into three folds. First, we design and model of HTC system with multiple actuators to control the desired room temperature. Second, this research contributes the quantitative studies and constraints of the HTC system on how to accomplish the desired room temperature in real-time basis. Last, this research contributes the investigation of the effect of supervisory and PI controllers towards the HTC system through simulation studies.

The rest of this paper is organized as follows. Some state-of-the-art research works that are related to this paper are summarized in Section 2. Section 2 also reviews the motivation of this research. In Section 3, we describe the design and modeling of the hybrid temperature control system and its mathematical representations. The supervisor and PID controllers are also discussed in the Section 3. Simulation scenario, setup, results and analysis are presented in Section 4. Section 5 concludes this research work and states our future works.

2. Related Work and Motivation

2.1 Related Work

The following section reviews the previous works on the home automation system for controlling the temperature and the service platform of CPS applications in related to the home environment.

Many research and industrial works have been conducted in controlling the temperature of buildings and rooms with HVAC (Heating, Ventilation and Air-Conditioning) system. Such researches of intelligent control for the HVAC system can be found in [8], [9], [10] and [11]. For example, Witrant, et al. [8] propose a model-based feedback control strategy for indoor temperature regulation in buildings equipped with underfloor air distribution (UFAD). However, Homod, et al. [9] 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. [10] 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 [11]. They showed the simulation results through distributed control and building performance simulation software tools by run-time coupling with a case-study represented with respect to the same material properties used in construction.

Other researchers have developed the simulation platform of CPS application for home environment system. These were reported in [12], [13], [14], [15] and [16]. In particular, Wang [12] presents a ventilation control strategy for multi-zone variable air volume air-conditioner systems and an adaptive optimization algorithm for optimizing the fresh airflow rate to minimize the energy consumption. Lai, et al. [13] 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. [14] introduce an extension of existing software architecture tool, called Acme Studio, for the modeling and analysis of cyber-physical system at the architectural level. By defining three entities; the cyber domain, the physical domain and their interconnection, they illustrate the architectural modeling using CPS architectural style with the example of a temperature control system for two zones (rooms).

A few researchers have been considered the CPS approach for a wide-range application. For instance, Wan, et al. [17] review the existing research results in the area of energy management, network security, data transmission and management, model-based design, control technique, and system resource allocation. The CPS applications in [17] include medical devices and systems, assisted living, traffic control and safety, advanced automotive systems, energy conservation, and smart structure.

2.2 Research Motivation

A continual growth of the temperature control in a real time basis for the home environment system has led to the essential of CPS approach. On the other hand, the supervisory controller and PID controller have been studied extensively in the last decades that are dynamically used to control the desired room temperature against the environment changes. In our viewpoint, these two different research domains can be combined to control and monitor the temperature more efficient by considering the multiple actuators on a real-time basis. This is because there are extensive benefits in resource saving by carefully designing the HTC system. Besides that, we can extend our HTC system not only control the temperature, but also control other comfort parameters, such as humidity, light, and so on. Furthermore, our HTC system can dynamically keep the desired room temperature regardless of disturbance effect in physical system. To the best of our knowledge, there is no research has been conducted to propose the supervisory and PID controllers for temperature control with multiple actuators in the HTC system. This becomes our motivation to study and investigate the proposed HTC system in this paper.

3. Hybrid Temperature Control System

In this section, we explain the detail of HTC system. First, we explain the model of HTC system and its feedback control. Second, we formulate the room temperature and heat equations, which are applied to the HTC system. Last, we describe the supervisory and PID controllers for HTC system.

3.1 HTC System Architecture

Figure 1 shows the basic architecture of HTC system. In this architecture, cyber world and physical world are defined. To connect these two worlds, we use a communication network of WSAN. In particular, the WSAN comprises of two components: sensors and actuators. The sensors in the physical side send the information of the environment (dynamic room temperature, outside temperature) to the controllers (supervisory and PI). However, the actuators (air-conditioner and window) in the physical side perform the corresponding task according to the control signal send by the controllers to makes the changes of physical system. In this architecture, we use the idea from the design and implementation of cyber-physical control systems over the WSAN that is presented in [3].

The feedback control of HTC system is illustrated in Figure 2. In this HTC system, the room temperature parameter is periodically assumed to be sensed by the sensors. These sensed data are sent to the PI and supervisory controllers. The PI controller computes an appropriate control input to be sent to the corresponding actuators. Similarly, the supervisory controller computes the appropriate control signal based on the changes of outside temperature and the feedback room temperature that continuously sensed by the sensors and then decides which action should be taken. By this way, the room temperature is being controlled and monitored to approaching the desired room temperature. The supervisory controller is designed in such a way to use the natural ventilation (opened window) instead of the air-conditioner when the outside temperature is lower than the inside temperature. In this HTC system, we also consider the number of occupants and solar gain through the window glass as the disturbances.

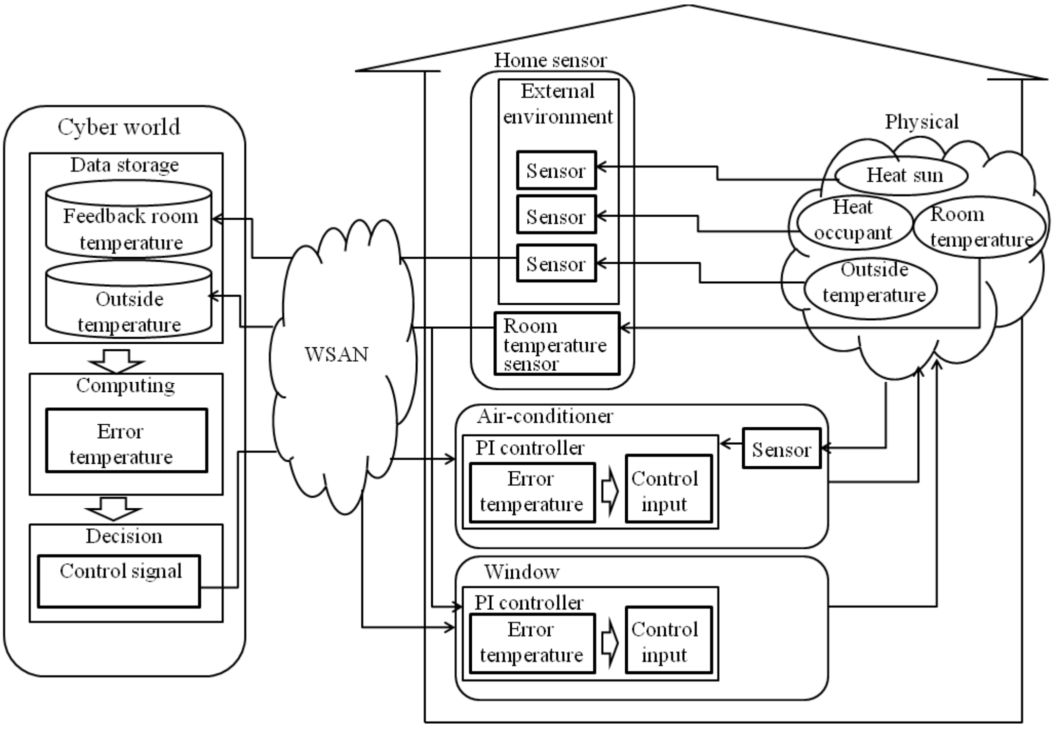


Figure 1. HTC system architecture.

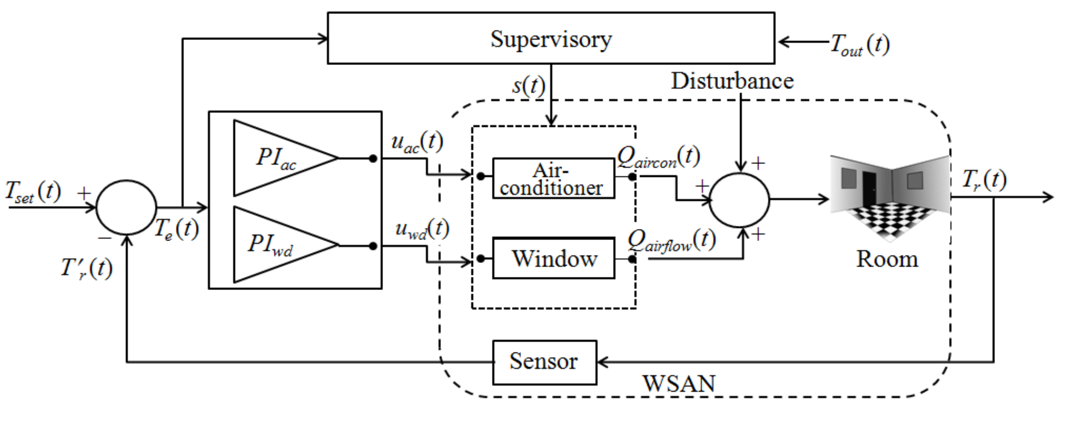


Figure 2. Block diagram of HTC system.

3.2 Mathematical Representation

The following section presents the mathematical representation of HTC system and explains the heat equations that are applied in the room temperature calculation. 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_{ss}), and the sensible heat gain and latent heat gain by occupants ($Q_{occupant}$). Therefore, a dynamic room temperature equation can be represented as

$$T_r(t) = \frac{1}{\beta} \sum Q_{all} + T_r(t-1) \tag{1}$$

where $\sum Q_{all}$=Q_{aircon}+$Q_{airflow}$+Q_{dth}+Q_{ss}+$Q_{occupant}$. We also define that β=ρ_{air} V_{room} C_p , where ρ_{air} is air density, V_{room} is room volume, and C_p is specific heat capacity air.

In the air-conditioner system, the circulation air serves as a carrier of heat and moisture either to or from the conditioner space. We can simply express the sensible heat in the heating or cooling system of air as follow

$$Q_{aircon} = 1.08 \times CFM(T_{sa} - T_r) \tag{2}$$

where CFM is air volume flow and T_{sa} is setting temperature of air-conditioner and T_r is room temperature.

When the window is opened, the heat generation of a space from outside to inside by the natural ventilation is given by

$$Q_{airflow} = V_{airflow} C_p \rho_{air} (T_{so} - T_r) \tag{3}$$

where T_{so} is supplied outside temperature. $V_{airflow}$ is ventilation rate required to remove heat from the occupied space. The airflow rate through ventilation inlet opening is $V_{airflow}$ = A_{op} c_d v_{air} where A_{op} is surface area of window opening, c_d is effectiveness of air, and v_{air} is air velocity leaving the opening.

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 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

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

where u_g is u-value for glass and A_g is surface area of glass window.

The heat gain when the sun shines through the window can be expressed as

$$Q_{ss} = F_c F_s A_g q_{sg} \tag{5}$$

where F_c is air node correction factor, F_s is shading factor for double glazing glass, and q_{sg} is tabulated cooling load.

Human beings release both sensible and latent heat to the conditioned space when they stay in it. Heat gain from occupant depends on the level of physical activity. The sensible and latent cooling loads for occupants staying in a conditioned space are calculated as

$$Q_{occupant} = (N \cdot SHG \cdot CLF) + (N \cdot LHG) \tag{6}$$

where N is number of occupants, SHG is sensible heat gain by occupants, CLF is cooling load factor for the occupants, and LHG is latent heat gain by occupants.

3.3 Supervisory Controller

Hybrid systems are dynamic systems that exhibit both continuous and discrete behaviors. The continuous time dynamics are modeled using differential equations whereas the discrete-event dynamics are modeled by finite state automata. Our HTC system is real-time systems. This means that decisions are taken synchronized with information arrival (occurrence of events). Hybrid automaton describing HTC system is shown in Figure 3. The room temperature is continuous dynamics whereas state transition is discrete nature. In this HTC system, we consider three discrete states; $S_{aoff,wcl}$, $S_{aon,wcl}$, $S_{aoff,wop}$. Supervisory controller computes the appropriate control signal with the predefined hybrid automaton. 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.

Hybrid automaton in Figure 3 can be represented as follows:

States = {$S_{aoff,wcl}$, $S_{aon,wcl}$, $S_{aoff,wop}$}

Inputs = {*error temperature*, *outside temperature*}
Outputs = {$Air\text{-}con_{on}$, $Air\text{-}con_{off}$, $Window_{open}$, $Window_{close}$}

The following differential equations govern the changes of the room temperature in the refinements of the three states.

When the system is in $S_{aoff,wcl}$ state, the room temperature changes according to following equation below

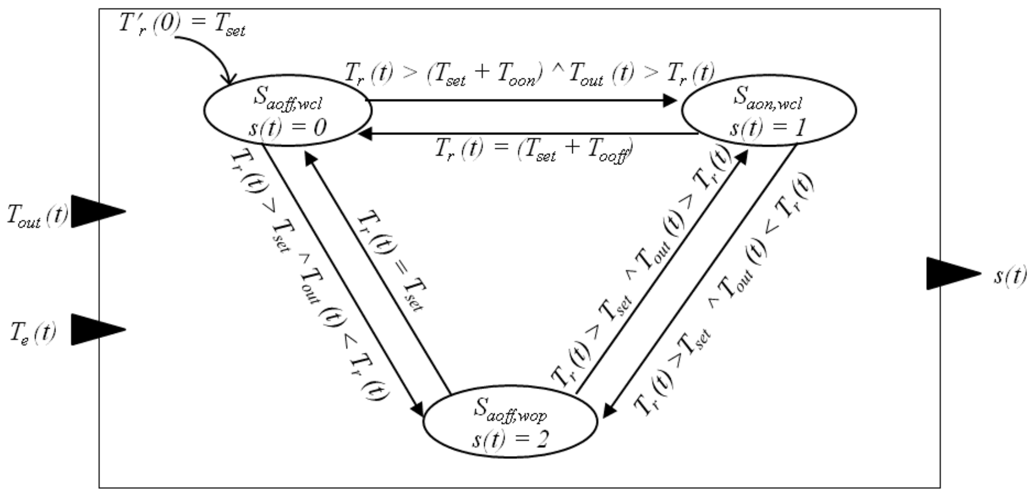
$$\frac{dT_r}{dt} = \frac{1}{\beta}(Q_{dth} + Q_{ss} + Q_{occupant}) \tag{7}$$

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

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

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

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



Actuators: Air-conditioner, Window	T_{oon} =offset temperature for air-conditioner is ON
Initial state: $S_{aoff,wcl}$	
$S_{aoff,wcl}$ = air-conditioner OFF & window CLOSED	T_{ooff} =offset temperature for air-conditioner is OFF
$S_{aon,wcl}$ = air-conditioner ON & window CLOSED	
$S_{aoff,wop}$ = air-conditioner OFF & window OPENED	T_{out}(t) = outside temperature
	$s(t)$ = status of switched control signal

Figure 3. Hybrid automaton describes the control of the desired room temperature.

3.4 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

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de}{dt} \qquad (10)$$

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, we consider the air-conditioner using a conventional PI controller and it varies the speed of the compressor motor, and controls the refrigeration load. For window, the PI controller controls the area of window opening. Firstly, PI parameters are calculated by using Ziegler-Nichols based on step response. Using MATLAB/Simulink toolbox, the parameters obtained is tested and the closest parameters to the practical value are used. The tuning parameters are: sampling period T_s= 1 second, $K_{p\text{-}ac}$=0.0051, $K_{i\text{-}ac}$=0.000143, $K_{p\text{-}wd}$=1.2020, and $K_{i\text{-}wd}$=0.00196.

4. Simulation Studies

4.1 Simulation Environment and Setup

In this section, we verify and examine how HTC system will behaves in real physical world by using computer simulation. In this simulation, we use the raw data from the experiments that were conducted at the smart house environment, which is located at Nomi city, Ishikawa prefecture, Japan. A photograph of the smart house, named *iHouse*, is shown in Figure 4. A detailed description of iHouse is available in Japanese version [18]. The measured outside temperature of the iHouse and the entered total heat from the sun through the windows of the living room during the summer season in July 2012 are used in our simulation. This work was accomplished by the aid of the home simulator presented in [19]. We also use the actual size of the iHouse for the HTC system, i.e., a living room with the size of 5.005 meters length, 4.095 meters width and 3.000 meters height. The living room has two small windows that face west and two big windows that face north. These four windows are mounted with automatic opened/closed motor. In the living room, one Mitsubishi-type (MSZ-ZW509S-W) air-conditioner is also available. Table 1 summarizes the other parameter types and values that are used in this simulation.

Figure 4. The smart house iHouse used in our simulations.

In our simulation, we use the MATLAB/Simulink tool and Java programming to implement and evaluate the HTC system model. Figure 5 depicts that the software architecture for our simulation environment of HTC system. In our program, we divide the simulation environment into five main modules; external environment (data storage), state manager, hybrid system interface, computation and output data. External environment that maintains the external environment data, e.g., the total amount of entered heat from the sun through windows, the emitted heat from the occupant and the outside temperature. State manager (supervisory) that computes the control signal according to the external environment data and feedback room temperature based on the predefined hybrid automaton for the HTC system (as illustrated in Figure 3). Meanwhile, the hybrid system interface module that translates the signal from the supervisory and then each PI controller calculates the control input value. In the computation module, the value of room temperature and power consumption of air-conditioner are calculated by using the output value from the PI controllers and the input data from the external environment. The computed results are shown in the output data module.

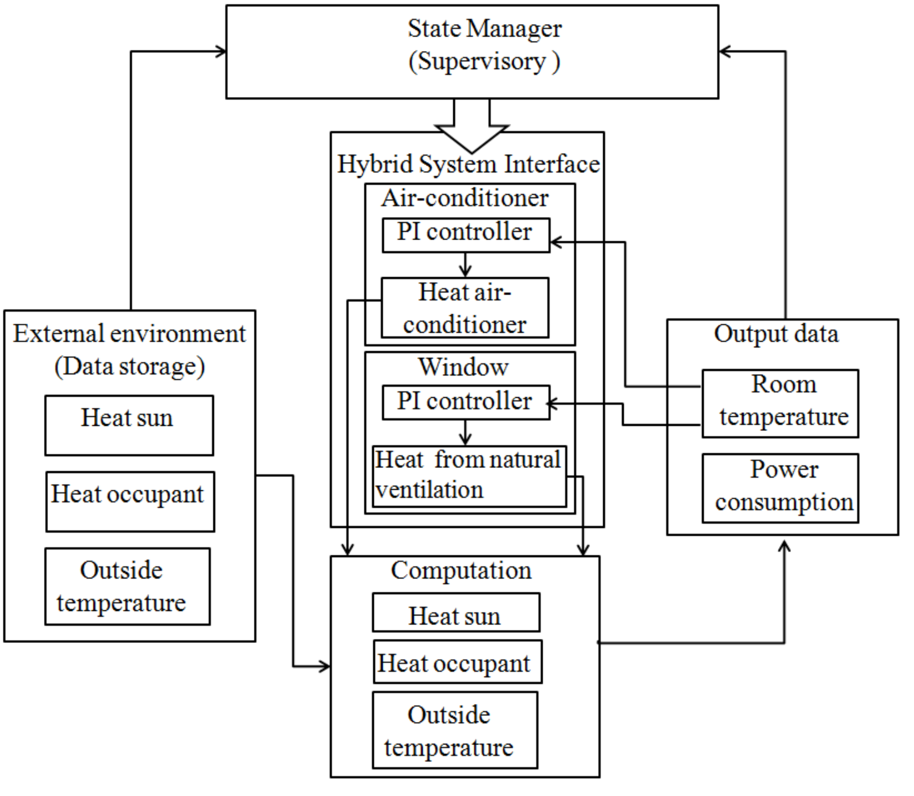


Figure 5. Software architecture for simulation environment.

Table 1. Simulation parameters and settings.

Parameter	Value
V_{room} (L×W×H)	5.005 m×4.095 m×3.000 m
ρ_{air}	1.2 $kg\ /\ m^3$
C_p	1.005 $kJ\ /\ kg\ ℃$
T_{set}	25 ℃
T_{sa}	22 ℃
T_{aon} (offset temperature for air-conditioner ON)	0.5 ℃
T_{aoff} (offset temperature for air-conditioner OFF)	0.5 ℃
Number of air-conditioner	1
Maximum cooling load	5 kW
COP	3.44

A_{g1} for north-facing window (L×W)	1.2 m×1.77 m
A_{g2} for west-facing window (L×W)	1.2 m×0.6 m
A_{op1} for north-facing window	2.124 m^2
A_{op2} for west-facing window	0.72 m^2
u_g	5.6 $W / m^2 °C$
c_d	0.61
SHG	230 Btu / h
LHG	190 Btu / h
CLF	1
K_{p_ac}	0.0051
K_{i_ac}	0.000143
K_{p_wd}	1.2020
K_{i_wd}	0.00196
Simulation time for day time	07:00 – 17:00
Simulation time for night time	19:00 – 05:00
State transition time for $S_{aoff,wcl}$ to $S_{aon,wcl}$	60 *seconds*
State transition time for $S_{aon,wcl}$ to $S_{aoff,wcl}$	1 *second*
State transition time for $S_{aoff,wcl}$ to $S_{aoff,wop}$	10 *seconds*

To evaluate our HTC system by using computer simulation, we divide our simulation into three parts. In the first simulation, we focus on finding the most acceptable Proportional-Integral (PI) gain values of the air-conditioner, named K_{p_ac} and K_{i_ac}. Then, the second simulation is to investigate how the room temperature is controlled by the HTC system without the supervisory control. In this second simulation, only one actuator (e.g., air-conditioner or windows) is operated in one time to control the room temperature. Meanwhile, we conduct the third simulation with the supervisory control. The supervisory control means that the room temperature is controlled by the air-conditioner and the windows simultaneously according to predefined hybrid automaton. Both second and third simulations are performed in two different scenarios: day time and night time. In third simulation, we use timer-based for regulating the closing of the window after it is being opened for a period of time. The purpose of the timer-based is to close the window if the window is failed to achieve the desired room temperature in a specific time. We define that the *window_closing_time* is one hour in our simulation. When the *window_closing_time* is reached, the windows are closing and the air-conditioner is ON, i.e., $S_{aoff,wop}$ state transits to $S_{aon,wcl}$ state. Both second and third simulations are also used the same amount of entered heat from the sun through the windows into the living room and the presence of occupant(s), which is showed in Table 2. In the last subsection, we discuss the energy consumption of the air-conditioner according to the simulations that have been conducted.

Table 2. The presence of occupant(s).

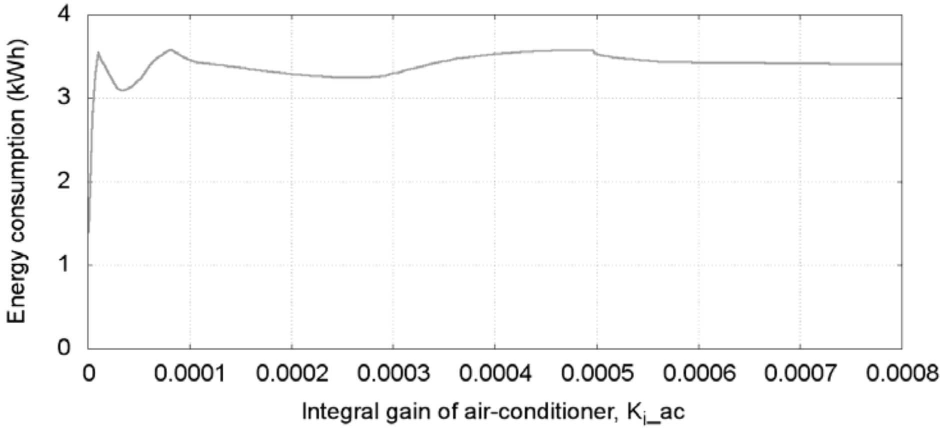
Time	No. of occupants
00:00 to 07:40	0
07:45 to 07:58	1
08:00 to 08:32	0
08:35 to 09:58	1
10:00 to 11:29	0
11:30 to 12:00	1
12:00 to 13:29	0
13:30 to 14:30	1

Time	No. of occupants
14:35 to 15:58	0
16:00 to 17:00	2
17:05 to 17:58	1
18:00 to 18:45	0
18:50 to 19:30	4
19:35 to 21:29	0
21:30 to 22:29	2
22:30 to 23:59	0

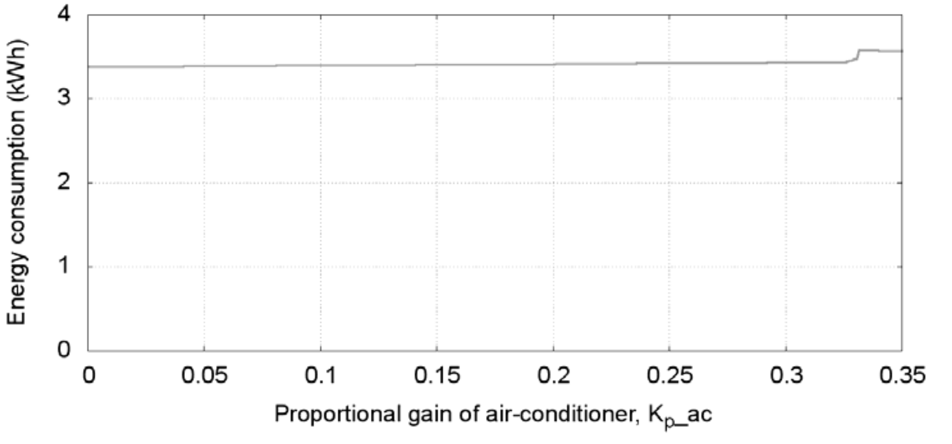
4.2 Simulation Results

4.2.1 Effect of Proportional-Integral (PI) Gain

Firstly, we analyze and choose the acceptable values of K_{p_ac} and K_{i_ac} (the gain values of PI controller) for HTC system based on the power consumption of air-conditioner that is approximately matched to the air-conditioner at the iHouse. We analyze the gain values of PI controller obtained from Ziegler-Nichols method and Simulink toolbox auto tuning. We observe that most of the gain values are impractical for our HTC system because the computed gain values contribute a larger power consumption of air-conditioner that is used in the iHouse. Figure 6(a) and Figure 6(b) show the relation between power consumption as a function of K_{p_ac} and K_{i_ac}, respectively. We can generally see that the increment value of either K_{p_ac} or K_{i_ac} makes not much change in the power consumption.



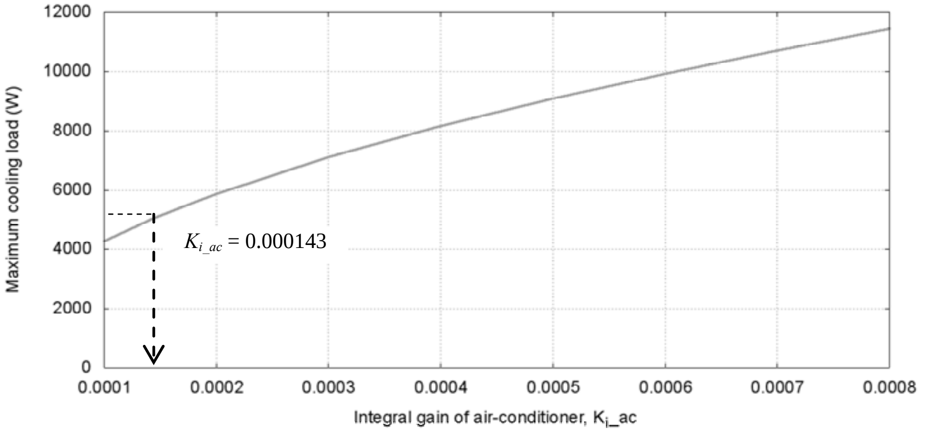
6(a). Energy consumption varies when K_{p_ac} is constant at the value of 0.0051.



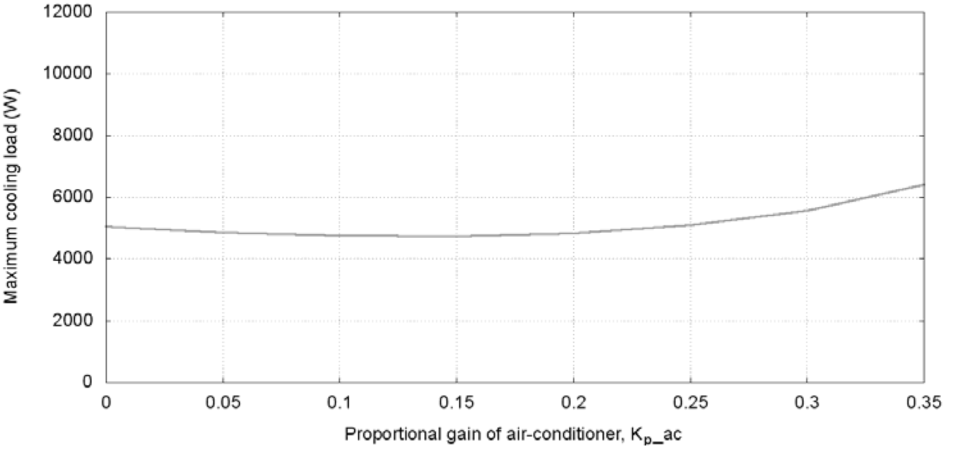
6(b). Energy consumption varies when K_{i_ac} is constant at the value of 0.000143.
Figure 6. Energy consumption of the air-conditioner.

On the other hand, Figure 7(a) and Figure 7(b) show the maximum cooling load and its gain value. It is seen that the increment value of K_{i_ac} makes the increase in the maximum cooling load, but not in the increment value of K_{p_ac}. To match properly the air-conditioner at the iHouse, we can observe the K_{i_ac} gain value in Figure 7(a) when the maximum cooling load of air-conditioner is about

5kW. We identify that K_{i_ac} is equal to 0.000143. We also show an example that the cooling load of air-conditioner with two different sets of K_{p_ac} and K_{i_ac} gain values, which are the best tuning gain values from Simulink toolbox in Figure 8. We realize that if we choose the right gain values, it leads to the cooling load never more than 5kW, i.e., K_{i_ac} is 0.000143 and K_{p_ac} is 0.0051.



7(a). Maximum cooling load varies when K_{p_ac} is constant at the value of 0.0051.



7(b). Maximum cooling load varies when K_{i_ac} is constant at the value of 0.000143.
Figure 7. Maximum cooling load of the air-conditioner.

4.2.2 Effect of Room Temperature without Supervisory Control

Figure 9(a) and Figure 10(a) show the changing of room temperature, number of occupants and the heat from the sun at the day time and at the night time, respectively. In Figure 9(a), it seems that although we could achieve the desired temperature by operating only air-conditioner, it is impossible to control the room temperature by opening only window at day time. However, we could achieve the desired temperature by opening only window at night time as illustrated in Figure 10(a) but it takes a very long time (about 7.5 hours). One main reason is that the real room temperature of iHouse is set as the initial room temperature in the simulation, which is too high. This leads to a longer time for windows to cool down the room temperature at the night time.

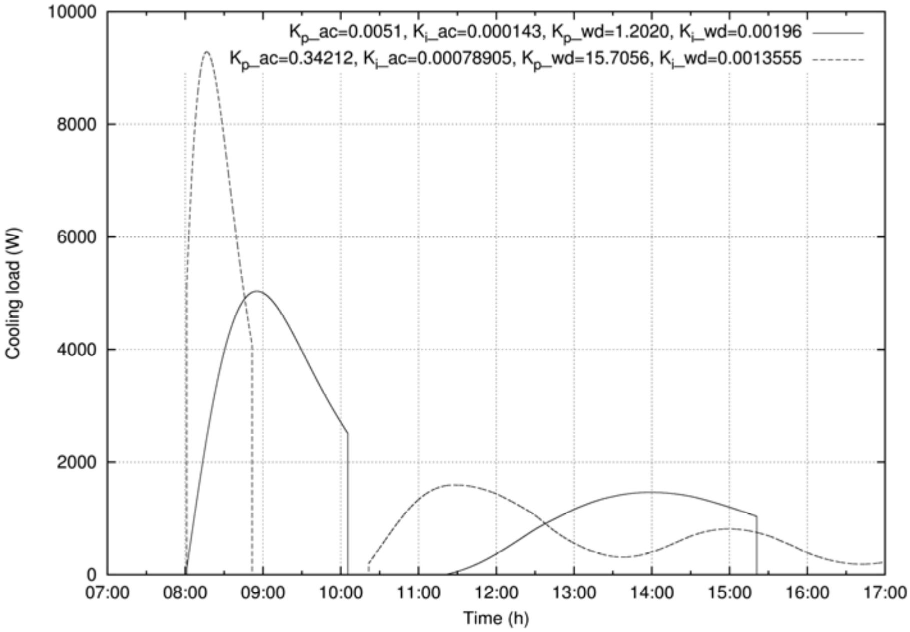
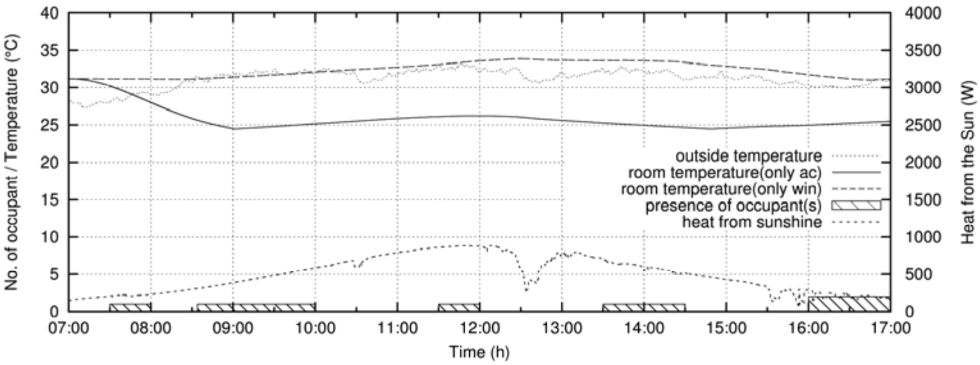
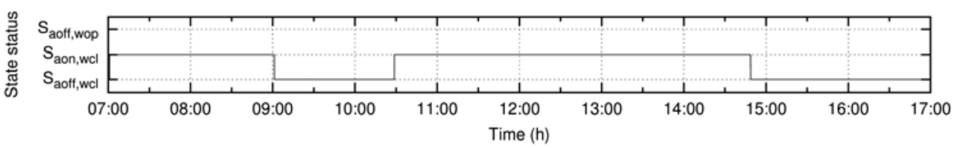


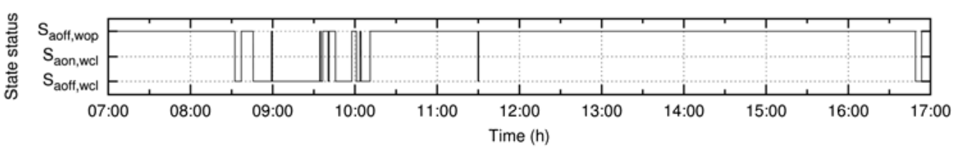
Figure 8. The cooling load of air-conditioner



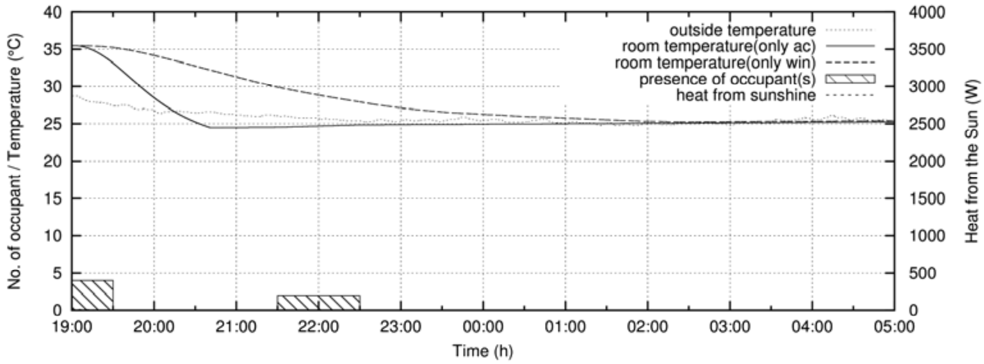
9(a). Change of the room temperature, the number of occupants and the heat from the sun.



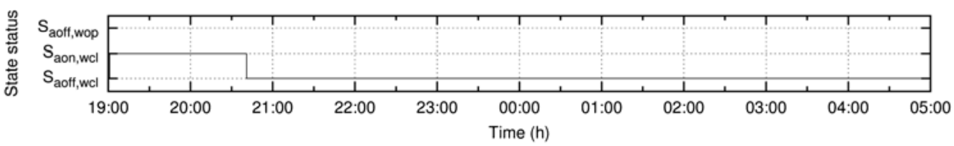
9(b). State status of the air-conditioner.



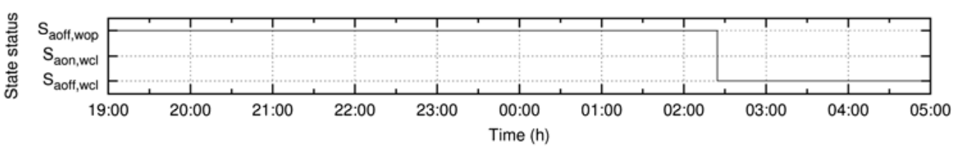
9(c). State status of all the windows.
Figure 9. Simulation results without supervisory control for day time.



10(a). Change of the room temperature, the number of occupants and the heat from the sun.



10(b). State status of the air-conditioner.



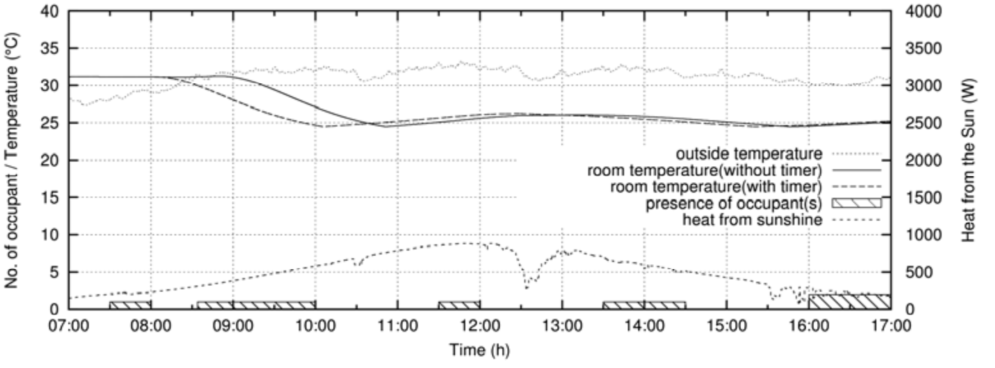
10(c). State status of all the windows.
Figure 10. Simulation results without supervisory control for night time.

4.2.3 Effect of Room Temperature with Supervisory Control

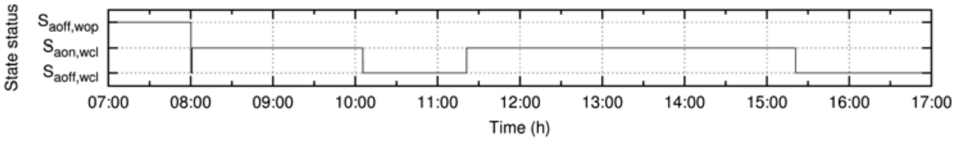
The simulation results for HTC system of a room with supervisory control at day time and at the night time are showed in Figure 11(a) and Figure 12(a), respectively. In Figure 11(a), we can see that the desired room temperature can be achieved faster with timer-based than without timer-based. This is because the HTC system is unable to control the room temperature with the opening window within one hour. We also observed that the system was unable to control the room temperature for a small duration (round 12:00 noon) when the large disturbance occurs (i.e., the heat from the sunshine and the heat from occupants) even the air-conditioner is operating at that moment. Because the air-conditioner considered in HTC system has the capacity constraint. In such case, we can consider a higher cooling load of air-conditioner if the user prefers to attain the desired room temperature quickly. We also observe that the amount of heat entered from the sunshine through the windows has a large influence in the room temperature. It prolongs the time to reach the desired room temperature. Similarly, it seems that the desired room temperature can be accomplished faster with timer-based whereas it takes longer to reach the desired room temperature without timer-based at night time as depicted in Figure 12(a).

4.2.4 Energy Consumption Comparison

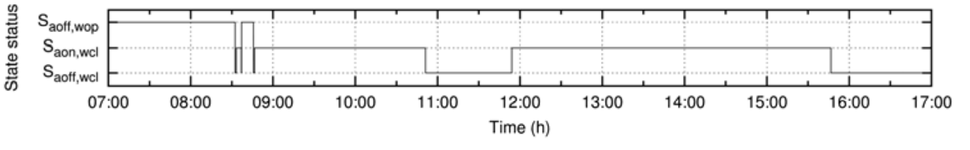
Figure 13(a) and Figure 13(b) show the energy consumption of air-conditioner for different scenarios at the day time and at the night time, respectively. In Figure 13(a), we can observe that the power



11(a). Change of the room temperature, the number of occupants and the heat from the sun.



11(b). State status with timer-based.



11(c). State status without timer-based.
Figure 11. Simulation results with supervisory control for day time.

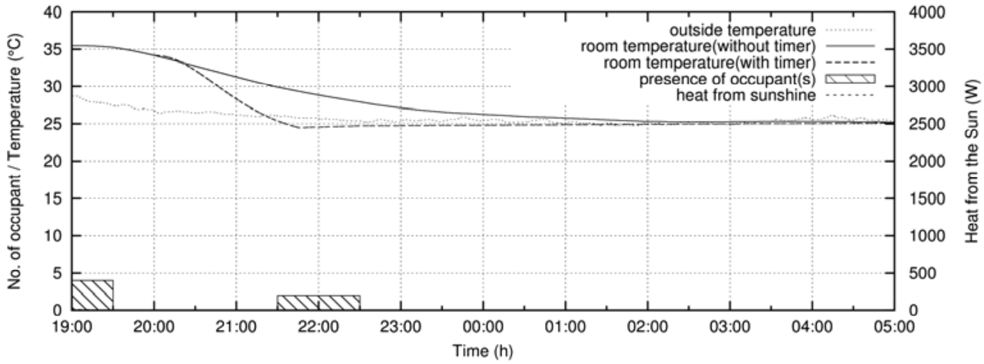
consumption difference of air-conditioner in between all the scenarios is very small. This is because the opening window could not help to reduce the room temperature in day time during the summer season. However, we could reduce the power consumption of air-conditioner when the supervisory controller without timer-based is applied at night time. But, it takes a long time to achieve the desired temperature. Since the power consumption is totally depending on the amount of cooling load that is provided by the air-conditioner. When the error temperature is large, the air-conditioner requires a higher cooling load, and it leads to the energy consumption becomes high. The energy consumption (*kWh*) of air-conditioner is calculated as below

$$P(t) = \frac{\int Q_{aircon}(t)dt}{COP} \tag{11}$$

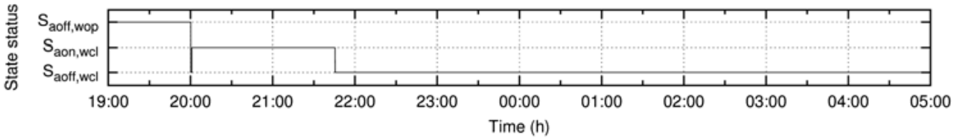
where Q_{aircon} is the cooling load of air-conditioner (*W*) and COP is the coefficient of performance. COP is assumed as a constant value that is listed in Table 1.

4.3 Discussions

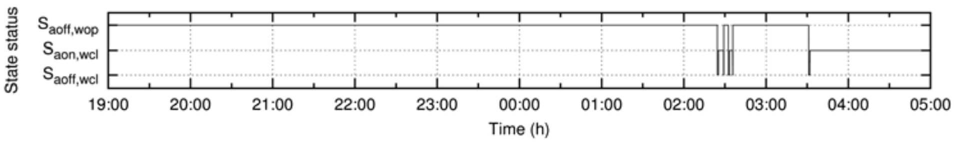
Although the HTC system is successfully implemented and verified, we still face a few things to improve. First, the HTC system will be inefficient because of the frequent of opening and closing the windows as depicted in Figure 9 (c). We have to consider more intelligent HTC system (e.g., we define the required outside temperature for opening the window together with timer-based along with the priority of user satisfaction). Second, we neglect the energy consumption of the motor to open/close the windows in this research. If the HTC system behaves abnormal, e.g., opening/closing



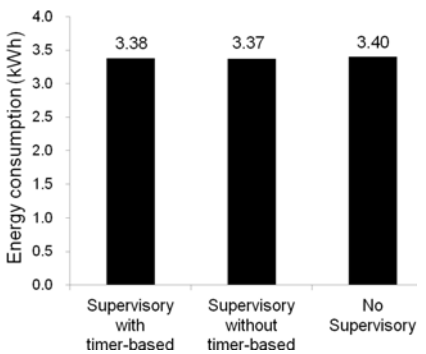
12(a). Change of the room temperature, the number of occupants and the heat from the sun.



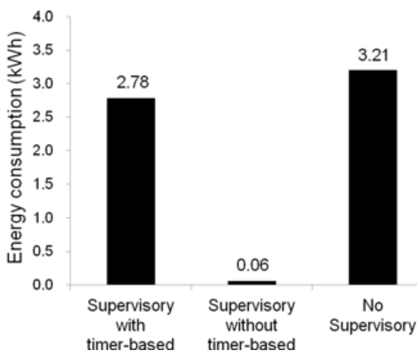
12(b). State status with timer-based.



12(c). State status without timer-based.
Figure 12. Simulation results with supervisory control for night time.



13(a). Day time.



13(b). Night time.

Figure 13. Comparison of the energy consumption.

the windows is too frequent, then we definitely need to consider for energy consumption of opening/closing the windows through the motor. Third, the HTC system is unable to control the room temperature for a short period when the disturbances are occurred (see Figure 9(a) and Figure 11(a), around 12:00 noon). The room temperature is slightly getting higher even air-conditioner is turned on. At that time, we can see that the outside temperature and the heat entered through the glasses are the peak value. In other words, the HTC system has the heat capacity constraint. To address this problem, we need a higher cooling load for the air-conditioner in order to attain the desired room temperature faster upon the user preference. Fourth, the opening window is incapable to cool down the room temperature for the summer season at the day time. Therefore, we need to consider another low cost actuator (e.g., ceiling fan) that might help to reduce the operation time of air-conditioner. Fifth, it seems that the energy consumption of air-conditioner between the timer-based and no timer-based at the day time is not too much difference. This is because the air-conditioner has to use more cooling load at initial operation time in both scenarios. To save energy, we have to understand that the energy consumption is depending mainly on how much cooling load is used, not for how long the air-conditioner is operated.

5. Concluding Remarks

In this paper, we have addressed the design and modeling of HTC system that is composed with the supervisory and PI controllers. Besides that, we have studied how the room temperature is controlled by multiple actuators in our proposed HTC system during the summer season. We also investigated the effect of PI controller on the HTC system. In similar, we showed that the supervisory control could reduce the energy consumption of air-conditioner. To the best of our knowledge, this research is the first attempt of real-time controlling room temperature using the CPS approach. From this study it can be concluded that our HTC system is very encouraging and extendable. For the future works, we will consider the room temperature control of HTC system with more actuators (e.g., fan, heater, and so on). For real deployment, we will conduct the experiment works using the iHouse facility. Further research is required to find out an optimization algorithm to optimize the multiple resource costs.

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