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

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***Abstract*—Nowadays, the need of temperature control at home is significantly demanded as the current controller used in buildings are not efficient and enough flexible to be adapted to any changes. In this research, we are focused on controlling two actuators (i.e., air-conditioner and window) using a PID controller and a hybrid controller during the summer season. We model the home temperature control (HTC) system, which is applied to monitor the desired room temperature all the times with optimal resource cost. The objective of this research is to investigate how the PID controller and the hybrid controller maintain the desired room temperature with only two actuators and minimal resource cost. In addition, we also aim to develop the practical application of cyber-physical system (CPS) for HTC system. Through MATLAB/Simulink simulation, we study and verify our proposed CPS-based HTC system.**

***Keywords*-home networks; cyber-physical system; PID controller; hybrid controller; multiple actuators**

I. Introduction

Since the need for comfort control at home is widely recognized nowadays, control of thermal environments is needed from the standpoint of comfort, health 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. We correlate the room temperature with the two actuators: air-conditioner and window.

The control of room temperature is a challenging task for the reasons of (1) changing the outside temperature in times which is used for one of the energy resource for controlling room temperature; (2) the delay time to get the user's preference room temperature; and (3) the dynamic of the process varies depending on the environmental conditions. While controlling the temperature of building and rooms with HVAC (Heating, Ventilation and Air-Conditioning) systems have been studied extensively in the last decades [1], [2], [3], [4], dynamically controlling the desired room temperature against the environment changes (cyber-physical system approach) with considering the hybrid control of the actuators that makes the conservation of desired room temperature in an energy efficiency way have not yet been studied much.

Wang [1] presents a ventilation control strategy for multi-zone variable air volume air-conditioning systems and an adaptive optimization algorithm for optimizing the fresh air flow rate to minimize the energy consumption. Witrant et al. [2] propose a model-based feedback control strategy for indoor temperature regulation in buildings equipped with underfloor air distribution (UFAD). Raijal et al. [3] investigate the window opening data from extensive field surveys in UK office buildings. Their research told that the mean indoor and outdoor temperatures when the window was open were higher than when it was closed, but there was a useful cooling effect from opening a window. Moreover, the temperature difference between the windows open and closed is small in a heavyweight building. Yahiaoui et al. [4] introduce the design of embedded control systems for integrated building plant.

CPS in [5] is integrations of computation with physical processes. In which embedded computer and networks monitor and control the physical processes, usually feedback loops where physical processes affect computations and vice versa. In the physical world, the system is dynamics, the evolution of its state over time. In the cyber world, dynamics is reduced to sequences of state changes without temporal semantics. Many researchers [5], [6], [7], [8], [9], [10] explain the characteristics and features of CPS in terms of specification, design challenges, construction, verification and analyzing challenges of CPS.

Wan et al. [12] review some major differences mobile ad hoc network (MANET), wireless sensor network (WSN), and CPS. They also explain some CPS platforms and systems that have been developed recently. Then, they explain how CPS applications exploit the physical information collected by WSN to bridge real and cyber space and identify important research challenges related to CPS designs. Xia et al. [13] explain the difference of general WSN apart from the wireless sensor and actuator network (WSAN), which will be one of the most critical technologies for building CPS. General WSN is used for information gathering in applications like habitat monitoring, military surveillance, agriculture and environmental sensing and health monitoring. The primary function of such WSN is to sense and monitor the state of the physical world. In most cases, they are unable to affect the physical environment. In many applications, however, it is not sufficient to just observe the state of the physical system; it is also expected to respond to the sensed events/data by performing corresponding actions upon the physical system. In [13], they distribute the topic of designing and implementation of cyber-physical control systems over WSAN and presents feedback control of CPS. The main idea of this feedback cyber-physical control architecture is to exploit measurements of the system's outputs to determine the control commands that yield the desired system behavior. 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 control commands, and send them to actuators. The actuators perform actions onto the system to effect the desired change. This feedback cyber-physical control system is applied to our proposed home temperature control (HTC) system for controlling desired temperature timely.

We model the HTC system with the characteristics of CPS explained in [5], [6], [7], [8], [9], [10]: they perform discrete computations, they deal with continuous quantities, they are concurrent and they run timelessly. In our proposed cyber-physical home system, the room temperature is always sensed by the sensors and this sensed value is compared with desired temperature. Then the controller will regulate to our desired temperature by controlling multiple actuators. We design the HTC system consisting of hybrid controller that controls the two actuators (air-conditioner and window) and PID (Proportional, Integral, and Derivative) controller.

This research aims to present the design of CPS-based HTC system consisting of hybrid controller and PID controller. It contributes developing practical and realization of CPS approach for home system to continuous monitoring and controlling the desired temperature regardless of dynamic environment changes. Moreover, we show our attempt of controlling the desired room temperature with two actuators with the aim of reducing the resource cost. To understand and analyze how our HTC system control the desired room temperature, we have developed a simulation with MATLAB/Simulink programming.

The rest of this paper is organized as follows. Research background that is related to this paper is summarized in section II. In section III, we describe the model of our HTC system and mathematical representation. Numerical results and analysis are presented in section IV. Finally, we conclude our research work and future work in section V.

II. Background and Motivation

A. Cyber-physical System

As explains in [8], the difference of CPS from the traditional embedded systems is that CPS is mainly designed for connecting physical devices to build an interaction network. The common way to build CPS is that sensors and actuators are embedded into electronic devices. The information of environment and electronic devices collected by sensors will be sent to the Decision Making System (called controller) or the user by the existing WSN techniques, such as routing, data gathering, and MAC protocols. Upon receiving the information, the controller or the user analyzes the collected information and then give back the decision to the actuators by a sequence of control processes, controlling the electronic devices to perform the corresponding task. Since Wireless sensor and actuator networks are the bridge between the cyber and physical worlds, they play an essential role in cyber-physical control systems. The special characteristics of CPS in [5] are: CPS models must stand for physical world, sensors and actuators, hardware platform, software, network and control system. It also must incorporate timing, concurrency and dynamics.

It is believed that in both the academic and industrial communities that CPS will have great technical, economic and societal impacts in the future. In recent years, CPS becomes a very active research filed for engineers and researchers because of their complexities: an convergence of sensing, control, computing, communication. The applications of CPSs in [12] include medical devices and systems, assisted living, traffic control and safety, advanced automotive systems, process control, energy conservation, environmental control avionics and aviation software, instrumentation, critical infrastructure (such as power and water), distributed robotics, weapons systems, manufacturing, distributed sensing command and control, smart structures, biosystems, and communications systems. In particular, there is only limited work in temperature control system with multiple actuators in Home Network targeting cyber-physical control applications.

Some related researches are efficient energy management in building structures. Wan et al. [8] discuss networked building control systems (such as HVAC and lighting) and it makes significantly improve energy efficiency and demand variability, reducing our dependence on fossil fuels and our greenhouse gas emissions. Zhao et al. [15] explore a conceptual framework of the CPS for energy management in the residential and commercial buildings sector in US. Kleissl et al. [16] contribute the examination of different types of buildings and their energy use and opportunities available to improve energy efficient operation through various strategies from lighting to computing. Using a modern 150,000 square feet office building as a closed system, they detail different strategies to reduce energy use from light emitting diode (LED) certification to zero net energy use. Karnouskos [17] discuses CPS as an integral part of the smart grid: an ecosystem which will heavily rely in its basis on (real-time) information acquisition (monitoring), assessment and decision making as well as management (control). Karnouskos indicates the vital role of CPS in smart grid. In contrast to existing CPS-based smart buildings, this paper develops the application of CPS-based for the HTC system with the multiple actuators and cost of energy regardless of dynamic environment changes.

B. PID Controller

PID controller, which consists of proportional, integral and derivative elements, is widely used in feedback control processes. PID controller monitors the system and computes the decision through the examination of feedback signals, which send by the sensors. Bi et al. [18] mention that as in other industrial applications, 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 PI/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 regulate near the balance setpoint, where its integral action can finally cancel the error. PID algorithm is described as

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \tag{1}$$

where $u(t)$ is the control signal, K_p is proportional gain, K_i is integral gain, K_d is derivative gain, and $e(t)$ is the control error.

The following Table. I shows the effects of increasing each of the controller parameters K_p, K_i and K_d.

Table I
EFFECTS OF INCREASING K_p, K_i, OR K_d PARAMETER INDEPENDENTLY

Parameter	Rise time	Settling time	Steady-state error
K_p	Decrease	Small change	Decrease
K_i	Decrease	Increase	Decrease significantly
K_d	Minor decrease	Minor decrease	No effect in theory

C. Hybrid Controller

Hybrid controller is a dynamical controller where the behavior of interest is determined by interacting continuous and discrete dynamics. Nevertheless hybrid controller is difficult to analyze. On the other hand, the reason for using the hybrid controller is that it gives better performance than ordinary systems and it can solve problems that can't be dealt with by conventional controller [19], [20]. Using the hybrid controller, we can combine several control algorithms and thus the hybrid controller that consists of several subcontrollers, each designated for a special purpose may be created.

Our hybrid controller for HTC system involves four components: the plant, the room temperature that is to be controlled, the sensors that measure room temperature, and outside temperature of the plant. The hybrid controller that determines the mode transition structure (the transition between actuators: air-conditioner and window) and the low-level controller: the actuators that make the changes of room temperature in cooperating with the PID controller. The details of the hybrid controller for HTC system are explained in section III.C.

III. HOME TEMPERATURE CONTROL SYSTEM

A. HTC System Model

In this section, the model of home temperature control system for summer is introduced. Fig. 1 shows the overview of home temperature control system. In this system, the room temperature is always sensed by the

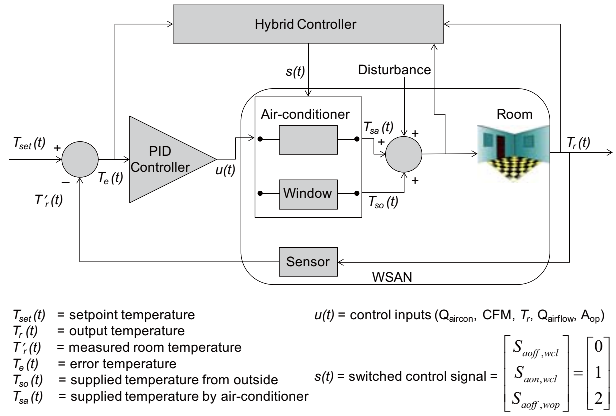

Figure 1. CPS-based home temperature control system

sensors, which send the measured data to an adder. Then the adder compares it against the desired value and sends the error temperature to a PID controller. The PID controller computes an appropriate control signal to be sent to the actuator(s) (i.e., air-conditioner and/or window). The changes of output temperature will be measured by sensors, which feedback to the adder. By this way, the room temperature is being controlled to approaching the desired temperature. A hybrid 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. The hybrid controller makes decision which action should be taken depending on the inside/outside temperature conditions and the feedback measured room temperature. In this system, we also consider the number of occupants and solar gain through the window glass as the disturbances.

B. Mathematical Representation

In this section, we present the mathematical representation of the HTC system and explain the heat equations that are applied in room temperature calculation. A dynamic room temperature equation can be represented as

$$T_r(t) = \frac{1}{\xi} \sum Q_{all} + T_r(t-1) \tag{2}$$

where, $\sum Q_{all} = Q_{aircon} + Q_{airflow} + Q_{dth} + Q_{ss} + Q_{occupant}$. Q_{aircon} is heat gain from air-conditioner, $Q_{airflow}$ is heat gain from opening the window, Q_{dth} is heat gain due to the temperature difference between inside and outside through window only, Q_{ss} is heat gain due to the sun shines through window only, and $Q_{occupant}$ is sensible heat gain and latent heat gain by occupants. We also define that $\xi = \rho_{air} V_{room} C_p$, where ρ_{air} is air density, V_{room} is room volume, and C_p is specific heat capacity air.

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

$$Q_{aircon} = 1.08 \cdot CFM \cdot (T_{sa} - T_r) \tag{3}$$

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

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

$$Q_{airflow} = V_{airflow} \cdot C_p \cdot \rho_{air} \cdot (T_{so} - T_r) \tag{4}$$

where T_{so} is supplied outside temperature, T_r is room temperature respectively, $V_{airflow}$ is ventilation rate required to remove heat from the occupied space. The airflow rate through ventilation inlet opening is $V_{airflow} = A_{op} \cdot c_d \cdot v_{air}$ 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 shining through windows. Heat gain through the glass due to the temperature difference between outside and inside can be expressed as

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

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

$$Q_{ss} = F_c \cdot F_s \cdot A_g \cdot q_{sg} \tag{6}$$

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

3) Occupant: 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

$$Q_{occupant} = (N \cdot SHG \cdot CLF) + (N \cdot LHG) \tag{7}$$

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.

C. Transfer Function

In this section, we describe the formulation of transfer function of the HTC system. We derive the transfer function of HTC system for two scenarios: using air-conditioner to control the room temperature and using opened window to control the room temperature. When air-conditioner is used, the change rate of room temperature is given by

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

Thus, the closed loop transfer function of HTC system with air-conditioner is written as

$$G_r^a(s) = \frac{MC_{ac}}{s^2 + C_r^a s + MC_{ac}} \tag{9}$$

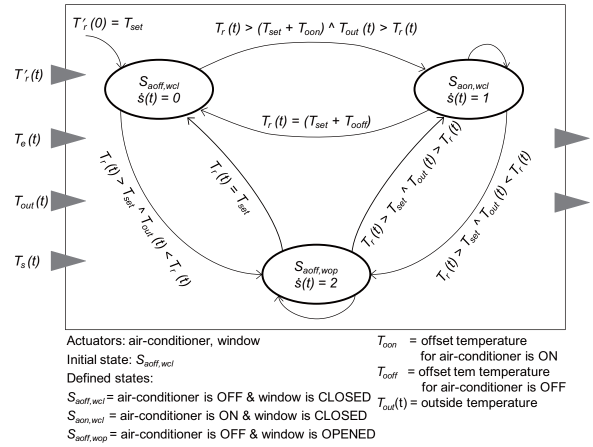

Figure 2. Hybrid Controller for home temperature control system

where $M = \frac{1}{\xi}$, $C_{dth} = u_g \cdot A_g$, $C_{ac} = 1.08 \cdot CFM$, and $C_r^a = M(C_{ac} + C_{dth})$.

Similarly, we formulate the transfer function for HTC system with opened window. When window is opened, the room temperature equation is governed by

$$\frac{dT_r}{dt} = \frac{1}{\xi}(Q_{airflow} + Q_{dth} + Q_{occupant}) \tag{10}$$

Thus, the closed loop transfer function of HTC system with opened window is expressed as,

$$G_r^w(s) = \frac{M(C_w + C_{dth})}{s^2 + C_r^w s + C_r^w} \tag{11}$$

where, $C_w = A_{op} \cdot c_d \cdot v_{air} \cdot C_p \cdot \rho_{air}$ and $C_r^w = M(C_w + C_{dth})$.

D. Hybrid Controller for HTC System

In this section, we present hybrid room temperature control system for summer season as shown in Fig. 2. In this system, we have three discrete states; $S_{aoff,wcl}$, $S_{aon,wcl}$, and $S_{aoff,wop}$. The continuous inputs are error temperature, measured room temperature, outside temperature, and heat supplied by the actuators. The output is the continuous room temperature and the control signal. The system initially starts at $S_{aoff,wcl}$ state. Here, we assume $T_r(t) = T_r'(t)$ The following differential equations govern the changes of room temperature in the refinements of the three states. They describe the low-level controller, i.e., the selection of time-based plant inputs in each state. When the system is in $S_{aoff,wcl}$ state, the room temperature changes according to following equation below

$$\frac{dT_r}{dt} = \frac{1}{\xi}(Q_{dth} + Q_{occupant}) \tag{12}$$

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

$$\frac{dT_r}{dt} = \frac{1}{\xi}(Q_{aircon} + Q_{dth} + Q_{ss} + Q_{occupant}) \tag{13}$$

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

$$\frac{dT_r}{dt} = \frac{1}{\xi}(Q_{airflow} + Q_{dth} + Q_{occupant}) \tag{14}$$

Table II
SIMULATION PARAMETER SETTINGS

$Vroom$ (L×W×H)	5.005 m × 4.095 m × 3 m
ρ_{air}	1.2 kg/m^3
C_p	1.005 $kJ/kg\,°$C
T_set	25 °C
T_sa	19 °C
T_oon	0.5 °C
T_ooff	0.2 °C
Number of air-conditioners	1
CFM	300 ft^3/min
Number of windows	4
A_{g1} for type 1 (L×W)	1.2 m × 1.77 m
A_{g2} for type 2 (L×W)	1.2 m × 0.6 m
A_{op1} for type 1	1 m^2
A_{op2} for type 2	0.456 m^2
u_g	2.8 W/m^2 °C
c_d	0.61
v_{air}	3.4 m/s
F_c	0.91
F_s	0.95
q_{sg}	238 W/m^2
Number of occupants	1
SHG	230 Btu/h
LHG	190 Btu/h
CLF	1
K_p^{PM} for day time	1
K_i^{PM} for day time	2.5
K_p^{AM} for night time	140
K_i^{AM} for night time	150

IV. NUMERICAL EVALUATION

To certify the design of the HTC system model, both experiment and simulation are performed in this research. In the experiment part, we conduct our experiment by measuring the outside and inside temperature of the iHouse facility, which is located at Nomi city, Japan. The measurement is taken in every 2 minutes during the summer season (the month of August). Our measurement also included when the air-conditioner at the living room of iHouse is turn on from 10:00 AM to 06:00 PM.

At the meantime, we use the MATLAB/Simulink software tool to evaluate our CPS-based HTC system model. In this simulation, we assume that one living room with four windows, which consists of two different types. The size of the living room and window is followed the actual size as in the iHouse facility. We use the measured raw data to certify our CPS-based HTC system model for 24 hours. Table II summarizes the parameter types and values used in the simulation.

Experimental and simulated results for HTC system of a room in day time and night time are shown in Fig 3 and Fig 4, respectively. it is seen that the closed-loop control is able to achieve the desired temperature in day time only. With hybrid controller, the closed-loop control can achieve the desired temperature in night time. In addition, the closed-loop control turn off the air-conditioner in day time if the desired temperature is achieved. This lead to less electricity consumption. Fig 5 show the electricity consumption for closed-loop control with and without hybrid controller. It can be seen that the hybrid controller can reduce the electricity consumption by about 44.75%. Furthermore, the hybrid controller consumes less energy in night time to achieve the desired temperature because the help of opening the window. From these simulation results, we can conclude that the role of hybrid controller is essential to trigger both PID controller and actuators to achieve the desired value with the most minimum resource cost.

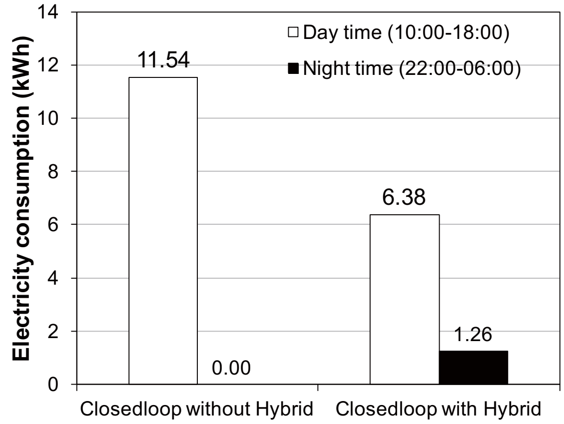

Figure 5. Electricity consumption comparison

V. CONCLUDING REMARKS

This study has introduced and investigated that the CPS-based HTC system can achieve favorable cost using hybrid controller with a well-cooperated in between the actuators. Our proposed CPS-based has been shown to have two obvious characteristic: one is the PID controller can be used to achieve the desired temperature faster; another is the the hybrid controller can be used to optimize the resource cost of the whole system. To the best of our knowledge, this is the first attempt of real-time controlling room temperature with CPS approach. For our future work, we will study the optimum value of PID gain with additional physical disturbances like number of occupants is increased. Moreover, we will find the optimization algorithm by minimizing resource cost.

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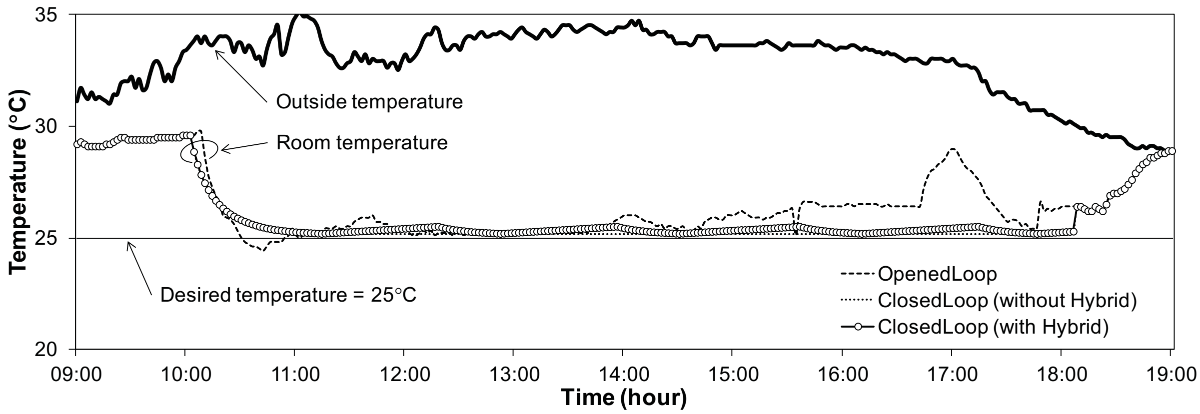

Figure 3. Experimental and simulated results for HTC system of a room in day time

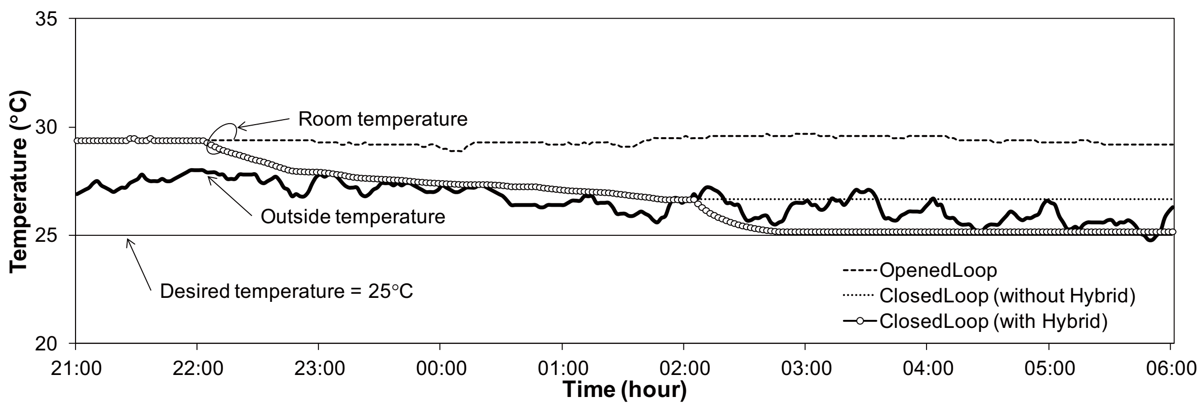

Figure 4. Experimental and simulated results for HTC system of a room in night time

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