Title	スマートホーム環境における複数のアクチュエータを用いたサイバーフィジカルシステムベース温度制御システムの設計と実装
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Design and Implementation of Cyber-physical Systems Based Temperature Control System with Multiple Actuators in Smart Home Environment

by

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Abstract

The temperature of the building may change according to a building's occupancy patterns, thermal process, the pollution and climatic changes in the surrounding environment. Therefore, control the building temperature is necessary to maintain indoor air quality and comfort requirements to provide a healthy and comfortable environment. Moreover, today people are seeking smarter and better buildings that make it easier for the habitants to manage the buildings more efficiently, reducing cost, and providing a better indoor environment. For those reasons, designing the smart control of heating, ventilation and air-conditioning system operation is critical to reduce the building energy consumption. In addition, the system needs to purse an acceptable compromise between comfort levels inside the residence and the costs associated with achieving that comfort.

Recently, the integrated control system composed with a set of controllers monitoring and controlling physical environment via a set of actuators, sensors and communication devices called Cyber-physical system (CPS) becomes more and more attention in a variety of different areas such as smart home, healthcare, smart transportation, etc. Therefore, creating the smart homes with CPS becomes an important trend of future development of quality of life and to create the energy-aware building with comfortable living.

This dissertation concerns research of technological issues for design and implementation, evaluation and optimization problem of one the application domains of CPS, called energy-aware temperature control system in this dissertation for the sake of explanation. The overall objective of this dissertation is to develop the application of CPS in smart home environment, which supports the reducing of energy consumption for heating and cooling operation while driving the system to desired temperature with the optimized control.

Design and implementation part addresses the basic components for proposed system model such as hybrid model, supervisory controller, PID controller, wireless sensor and actuator network. Then, the system is designed with the characteristics of CPS such as real-time sensing and computation, adaptability, autonomy and executing timeliness. The performance of the system is analysed in terms of room temperature regulation, thermal comfort and energy consumption by adding one by one actuator into the system. The simulation results show that even the natural ventilation could not help to reduce the internal heat gain in day time , it makes less power consumption of air-conditioner in the morning and at night time during summer season. Moreover, the power consumption of heating/cooling devices can be reduced with the interoperability among those actuators to achieve the desired temperature.

To evaluate the system, the validation of the system is shown with both simulation and experiment results. First, the real house based room temperature control simulator is developed with MATLAB/Simulink tool. Then, the system is implemented in real smart house, iHouse.

For the optimization problem of the system, parameter optimization of the state transition for multi-mode hybrid automaton is solved by using the particle swarm optimization (PSO) algorithm. First, a simple algorithm for preventing the visit to useless modes is presented. Following this, decision variables for mode transition are optimized by using PSO algorithm. Moreover, the computation load, quantization errors in the steady state and stabilization problem for the optimal control problem of model predictive control (MPC) for large-scale system is solved. The proposed method is applied in air conditioning system as one of the applications. With the proposed method, the computation time is reduced to 99.99% in compare with the existing method, MIQP (Mixed Integer Quadratic Programming) problem.

This proposed research can help the development of CPS applications in smart home environment and gives better solution for inhabitants who are seeking the thermal satisfaction with low cost.

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Chapter 1

Introduction

In recent years, the integrated control systems with computing, communication and controlling for active interaction between physical (e.g. electronic equipment with embedded sensors) and cyber (computational) elements, called Cyber Physical Systems (CPSs), have gradually attracted more and more attention in a variety of different areas. Today, a heating, ventilation and air-conditioning (HVAC) system in modern buildings can be represented as a prototypical CPS with deeply coupled embedded sensing, networked information processing and interaction with physical environment. Modelling a building temperature control system using CPS will play a vital role in reducing the cost for heating and cooling devices. This dissertation deals with design and implementation, evaluation and optimization problem of CPS-based temperature control system and its application to smart home environment.

1.1 Overview of Cyber-physical Systems (CPSs)

CPS combines components of the cyber world and the physical world to obtain a common goal and, through embedded computers systems, monitor and control the physical processes, usually using a network core and feedback loops, where the physical world affects the cyber system and vice-versa [1]. The main tools of CPS methodologies are computing, communications and controlling. CPS is an integration of physical dynamics and computational systems, so they commonly combine both discrete and continuous dynamics. Therefore modeling of cyber and physical processes can be viewed as hybrid

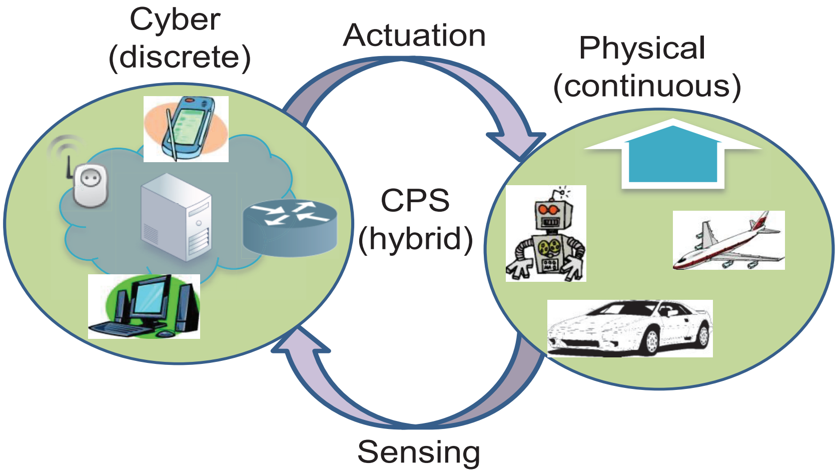


Figure 1.1: Architecture of Cyber-Physical System (CPS).

system modeling. Figure 1.1 shows the basic architecture of CPS.

The special characteristics of CPS in [2] are: CPS model must stand for physical world, sensors and actuators, hardware platform, software, network and control system. Obviously, CPS is different form desktop computing, traditional embedded/real-time systems, and WSNs (Wireless Sensor Networks). However, they have some different characteristics as defined in [3], [4]and [5]:

- ***Cyber capability in every physical component and resource constraint*:** The software is embedded in every embedded system or physical component, and the system resources (e.g., computing and network bandwidth) are usually limited.
- ***Closely integrated*:** CPS deeply integrates computation with physical processes.
- ***Networked at multiple and extreme scales*:** In CPS, the networks of which include wired/wireless network, Wi-Fi, Bluetooth and GSM, among others, are distributed systems. Moreover, the system scales and device categories appear to be highly varied.
- ***Complex multiple temporal and spatial scale*:** In CPS, the different components likely have unequal granularity of time and spatiality. CPS is strictly constrained by spatiality and real-time capacity.
- ***Dynamically recognizing/reconfiguring*:** CPS, as very complicated and large-scale systems, must have adaptive capabilities.

- ***Closed-loop control and high degrees of automation*:** CPS favor convenient man-machine interaction, and advanced feedback control technologies are widely applied to these systems.
- ***Operation must be dependable and certified in some cases*:** Reliability and security are necessary for CPS because of its extreme scales and complexities.

Some of the research challenges for CPS described in [13] are

- ***Control and Hybrid Systems*:** A new calculus must merge time-based systems with event-based systems for feedback control. This calculus must apply to hierarchies involving asynchronous dynamics at different time scales and geographic scope.
- ***Architecture*:** CPS architecture must be consistent at a meta-level and capture a variety of physical information. New network protocols must be designed for large-scale CPS. An innovation paradigm can be built around the notion of being "globally virtual, locally physical".
- ***Model-based Development of CPS*:** Models are used today to generate and test software implementations of control logic. Abstractions that cover the entire CPS design space must be developed, modified and integrated. Communications, computing and physical dynamics must be abstracted and modeled at different levels of scale, locality and time granularity.

1.1.1 Application Domains of CPS

It is believed that in both the academic and industrial communities CPS will have great technical, economic and societal impacts in the future. In recent years, CPS becomes a very active research field for engineers and researchers because of their complexities: a convergence of sensing, control, computing, and communication.

The review of the state-of-the-art design techniques from various angles and the research progress in the aspects of energy management, network security, data transmission and management, model-based design, control technique, and system resource allocation can be found in the technical survey paper [6]. The applications of CPS 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 communication systems [3] and [4].

The classic application architecture of CPS is described in [7]. Some application cases for CPS was conducted in [9] and [10]. Other relevant researches of CPS application for home environment system can be found in [8], [11] and [12]. Lai et al. [8] propose the OSGi-based service architecture for cyber-physical home control system, which supports service-oriented control methods. Duchon, et al. [11] introduce an extension of existing software architecture tool, 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 two zones (rooms).

Some related researches of efficient energy management in building structures can be found in [14], [15], [16] and [17]. [14] discuss networked building control systems (such as HVAC and lighting) and it makes significantly improve energy efficiency and demand variability, reducing the dependence on fossil fuels and the greenhouse gas emissions. [15] explores a conceptual framework of a cyber-physical system (CPS) for energy management in the residential and commercial buildings sector in US. [16] contributes 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. [17] discuses CPS as an integral part of the SmartGrid: an ecosystem which will heavily rely in its basis on (real-time) information acquisition (monitoring), assessment and decision making as well as management (control) and the author indicate the vital role of CPS in SmartGrid.

1.1.2 CPS versus Traditional Embedded System

The characteristics of CPS compared to embedded system are summarized as follows:

1. Cyber-physical system (CPS) is a tight combination of and coordination between,

the systems computational and physical elements. In embedded systems the emphasis tends to be more on the computational elements, and less on an intense link between the computational and physical elements. Unlike more traditional embedded systems, CPS is typically designed as a network of interacting elements with physical input and output instead of as standalone devices. The notion is closely tied to concepts of robotics and sensor networks [18].

2. In [19], embedded system has been used for some time to describe engineered systems that combine physical processes with computing such as in the applications of communication systems, aircraft control systems, automotive electronics, home appliances, weapons systems games and toys. However, most such embedded systems are closed boxes that do not expose the computing capability to the outside.

   Moreover, embedded software is software on small computers. The technical problem is one of optimization (coping with limited resources). In contrast, CPS is computation and networking integrated with physical processes. The technical problem is managing time and concurrency in networked computational systems.

   Cyber-physical system by nature will be concurrent. Physical processes are intrinsically concurrent, and their coupling with computing requires, at a minimum, concurrent composition of the computing processes with the physical ones. Even today, embedded systems must react to multiple real-time streams of sensors stimuli and control multiple actuators concurrently. Regrettably, the mechanisms of interaction with sensor and actuator hardware, built for example on the concept of interrupts, are not well presented in programming language.

3. In embedded systems, the emphasis tends to be more on the computational elements, and less on the link between the computational and physical elements.

1.2 Research Problem and Motivation

Extensive research efforts have been made to develop a variety of monitoring and controlling applications in smart home environment such as lighting control, environmental monitoring, energy management, devices control, security control, etc. In this dissertation, temperature control is considered one of the research problems of the smart home environment applications.

The temperature of the building may change according to a building's occupancy patterns, thermal process, the pollution and climatic changes in the surrounding environment. Moreover, today's people are seeking smarter and better buildings to achieve a comfortable living with less energy. Therefore, control the building temperature is necessary to maintain the indoor air quality and comfort requirements to provide a healthy and comfortable environment.

On the other side, according to recent studies in [104], energy consumption is increasing year after year, and if effective energy saving policies will not be adopted, in 2040 they will be double with respect to 2000 level. Similarly, [103] and [102] presents the energy consumption for houses in Japan. In Figure 1.2, we can see that the top residential end-uses of energy are: water heating, space heating and lighting. So, this survey have been interested by the research community as well as the industry world in the use of new generation home automation systems for energy saving. Their general goal is to approach the energy-aware building with comfortable living by reducing 58% of present energy use.

For those reasons, designing the smart control of heating, ventilation and air-conditioning system and considering the optimal control of the system are critical to achieve the low energy consumption without violating thermal comfort. One fundamental question that arises is how to reduce energy consumption for air conditioning system for homes and how to optimize the system.

Some of the current solutions for energy consumption in smart home are remotely controlling and programming the thermostat[105], room to room fan [105], program the shades to close during the brightest hours of the day [106], and ECO NAVI ventilation system and air conditioning [107].

Recently, the integrated control system composed with a set of controllers monitoring and controlling physical environment via a set of actuators, sensors and communication devices called cyber-physical system (CPS) becomes more and more attention in a variety of different areas such as smart house, healthcare, smart transportation, and so on.

In this dissertation, temperature control system for smart home environment is considered as CPS-based as explained in above paragraph. It is efficient to create the smart

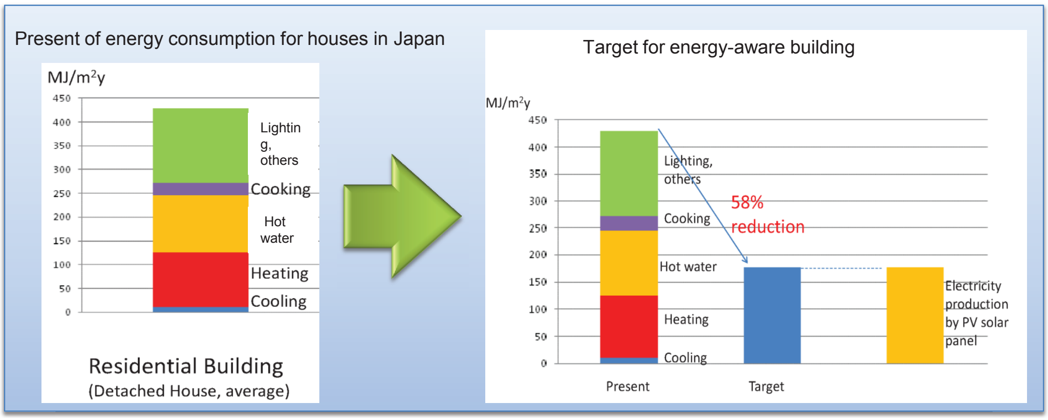


Figure 1.2: Energy consumption for houses [103].

homes with CPS-based for the future development of quality of life and to achieve the energy-aware temperature control system.

Application of CPS in temperature control system of such smart home is regarded with embedding sensors and actuators into electronic devices in daily life. The important aspect of CPS-based temperature control system is the seamless and complex interactions among the computing units and the physical world. For example, consider the temperature control system with multiple actuators as shown in Figure 1.3. The sensors periodically sense the room temperature and environment factors and send this information to the decision making system, called supervisory controller. Upon receiving the information, the decision making system analyzes the received information and then makes the decision that which actuator have to operate at each time. By integrating computation, communication and controlling components to achieve the real-time sensing and dynamic control, the energy efficiency can be dramatically improved while saving the energy consumption of heating/cooling devices.

However, some of the challenges in CPS are explained in [3] and [5]. From my point of view, to synthesis the optimal controller for CPS, the criteria such as the system model, the specification and the solution approach are important to consider. The complexity of CPS makes the design process hard, annoying and give the errors, but currently, there are non unified framework or formal methods can be used in most applications. Second, does the system would meet its specification; control objective? Different approaches provide different types of guarantees. For example, conditional guarantee, where the approach will find a correct solution if some conditions hold. Third is the solution approach. Depending

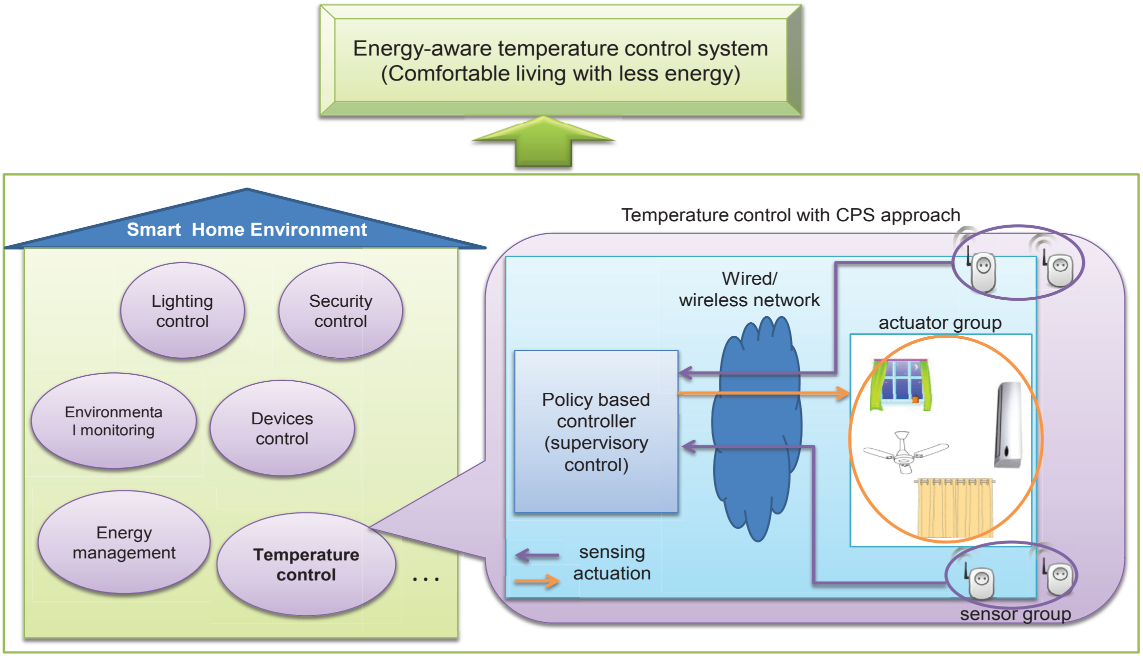


Figure 1.3: Towards energy-aware temperature control system via CPS.

on the system model and specification, different approaches and techniques have been used to solve the problem. Some approaches reduce the problem to an optimization problem.

For example, in the temperature control system, it is critical to consider the optimal control algorithm of the system that balances comfort and energy usage. As explained in [108] and [109] with the example of simple thermostat controller (see Figure 1.4), the system has three modes *OFF, HEAT, COOL* and two variables *temp, out* where *temp* is the room temperature and *out* corresponds to outside temperature. The dynamics of system is given in each mode, for example when the thermostat is in *HEAT* mode, the temperature of the room changes with rate $\dot{temp} = -0.1(temp - out) + 0.05(80 - temp)$.

The performance requirement is to keep the temperature as close as possible to the target temperature 20°C and minimize the consumption of fuel as much as possible. It is also required to minimize the wear and tear of the heater caused by switching. The guard g on the edges controls the switching between modes. A transition takes place as soon as guards on it are satisfied. Now the question is how to formalize these requirements and how to synthesize guards such that the system satisfies its requirements? Moreover, if we consider such kind of system consists of multiple actuators with continuous-valued input and discrete-valued control inputs for large scale system, the computation complexity for

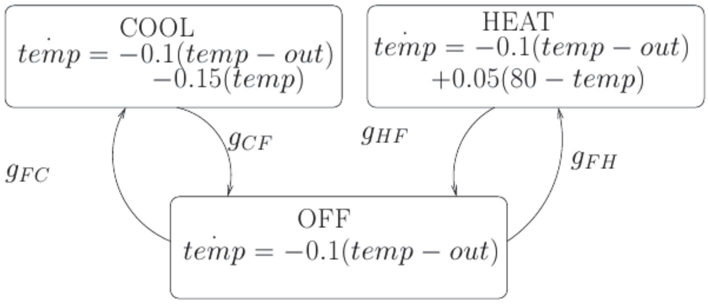


Figure 1.4: Thermostat controller.

optimization algorithm is one of the problems necessary to solve.

For those reasons, the research problems of this dissertation are

- design and implementation of CPS-based hybrid temperature control (HTC) system in smart home environment
- evaluation of the developed system to guarantee that the system meets its specification
- solving the optimization problem of the system.

Then, this dissertation is motivated with three main parts:

i. design and implementation
ii. evaluation
iii. optimization problem of the system

Design and implementation part addresses the basic components applied for system model such as hybrid model, supervisory controller, wireless sensor and actuator network and multiple actuators. The system is designed by adopting with the characteristics of CPS such as real-time computation, adaptability, autonomy and executing timeliness. Moreover, it is designed by means of the interoperability among the actuators in order to minimize the energy consumption of heating and cooling devices while ensuring the comfort of the residents. Here, an actuator is defined as an object that can potentially change the environment temperature through the thermal heat at the home, for instance, air-conditioner, heater, ceiling fan, window, curtain, etc.

The indoor temperature fluctuated by internal and external heat loads and the environment factors (e.g. outside temperature, the heat gain from the sun through the window) are always sensed by the sensors. With the closed-loop interactions, the indoor temperature is feedback to the supervisory controller through the wireless sensor actuator (WSANA) network. Upon receiving the information; feedback values and environment factors; the decision making system named the supervisory controller in this dissertation analyzes the collected information and then reflects the decision to the actuators by a sequence of control processes, controlling the heating and cooling devices to perform the corresponding task. Moreover, the air-conditioner is designed with conventional Proportional and Integral (PI) controller to regulate the air volume flow according to the error temperature and which is approximately matched to the air-conditioner equipped in experiment house, iHouse [21]. This CPS-based temperature control system is applied in smart home environment as one of the application domains of CPS.

To define the policies for operation of each actuator, the effect of low cost temperature control devices such as window for natural ventilation, curtain for preventing heat gain and heat loss through the window glass and ceiling fan for air circulation are studied. Different types of supervisory controllers are formulated based on the presence of occupant in the room. The performance of each controller is evaluated against the energy cost and the thermal comfort to achieve the desired temperature. The advantage of CPS-based HTC system over a common home temperature control system is that the system is designed with interoperability among the actuators along with the compromise between the user's preference and the energy cost.

In second part, evaluation of the system is conducted along with the simulation, experiments and implementation processes. For simulation, real house based room temperature control simulator is implemented in MATLAB/Simulink. For experiment, the system is implemented in real smart house. Then, the validation of the system is shown by comparing the simulation results with the experiment's.

Third part is regarded with optimization problem of the system. First, parameter optimization problem for multi-mode hybrid automaton is solved with the particle swarm optimization (PSO) algorithm. Following this, the problem of computation load, quantization errors in the steady state and stabilization problem for model predictive control (MPC) for large-scale system is solved. Then the proposed system is applied in temperature control system for multiple rooms as one of the applications.

1.3 Dissertation Objectives

Control the home temperature is necessary to maintain indoor air quality and comfort requirements to provide a healthy and comfortable environment. For those reasons designing the smart control of heating, ventilation and air-conditioning (HVAC) system operation is critical by reducing the building energy consumption. In addition, the system needs to purse an acceptable compromise between the comfort levels inside the home and the cost associated with achieving that comfort. In this aspect, CPS becomes one of the solutions to reduce the energy consumption of the appliances intelligently in the home. In contrast to traditional embedded systems, CPS interface directly with the physical world. By merging computing and communication with physical processes and mediating interaction with the physical world, CPS bring many benefits, including: making physical systems safer and more efficient; reducing the cost of building and operating physical systems; and allowing for individual machines to work together to form complex systems that provide new capabilities.

The purpose of this research is to develop the application of CPS technology in smart home environment, which supports the reducing of energy consumption for heating and cooling operation while driving a system to a desired temperature with the optimized control.

In particular, the research objectives are summarized as follows.

1. To develop the novel application of CPS in smart home environment, which resolves the usage of electricity problem for heating and cooling in home by allowing the users to
    - improve the thermal comfort of the habitants
    - reduce the monthly payment of electricity bills
    - live in better and smarter life-style and this leads to the increasing the quality of life.
2. To show the validation of the system by conducting both simulation and experiment in real smart house
3. To solve the optimization problem of

- parameter optimization problem of multi-mode hybrid automaton
- computation load, quantization errors in the steady state and stabilization of the model predictive control (MPC) of multiple rooms temperature control system

1.4 Dissertation Contribution

The contribution of this dissertation fall in three parts concerning respectively design and implementation, evaluation and optimization problem of CPS-based temperature control system in smart home environment. This dissertation can help the development of CPS application in smart home environment and give better solution for inhabitants who are seeking the thermal satisfaction with low cost. In this dissertation, the following specific contributions are made to advancing the state of the art in this area.

1. Presenting the design and implementation of CPS-based hybrid temperature control system with multiple actuators in smart home environment and studying the effect of low cost temperature control devices such as window, curtain and fan in room temperature control. Through simulation, the results show that those temperature control elements are compulsory to consider and the interoperability among the actuators could help for reducing the energy consumption.
2. Showing the validation of the model by conducting both simulation and experiment. For simulation, real house based room temperature control simulator is created and for conducting the experiment, the system is implemented in real smart house.
3. Presenting an algorithm for prohibiting the visit to useless modes for multi-mode hybrid automaton and solving its parameter optimization problem with PSO algorithm. Simulation results show that the temperature control with PSO algorithm gives better performance in the energy consumption and number of state transition times than the conventional controls.
4. Presenting a hierarchical implementation of MPC for large-scale systems with continuous-valued and discrete-valued inputs. In this study, computation load, quantization

errors in the steady state and stabilization of optimization problem for model predictive control (MPC) of large-scale system are solved. Moreover, the application of proposed system in the air-conditioning system is presented.

1.5 Dissertation Outline

This dissertation is progressed by the following steps:

Step 1. Introduction of the dissertation background, research problem and motivation, dissertation objectives and contributions in Chapter 1.

Step 2. Related knowledge of this dissertation such as smart homes, traditional temperature control system and CPS-based temperature control system, supervisory control, optimization problems in temperature control system and thermal comfort in Chapter 2.

Step 3. Design and implementation and the evaluation of the system with four actuators: air-conditioner, window, curtain and fan in Chapter 3.

Step 4. Evaluation of the system by conduction the experiments in iHouse in Chapter 4.

Step 5. Parameter optimization problem for multi-mode hybrid automaton in Chapter 5.

Step 6. Optimization problem for MPC of multiple rooms temperature control system in Chapter 6.

Step 7. Summary of the dissertation and discussion of future research directions in Chapter 7.

Chapter 2

Research Background

2.1 Introduction

Since the essential for comfort control of home is widely recognized nowadays, the smart control of thermal environment 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 the same time, it is important to decrease the energy consumption in air-conditioning system in the intelligent buildings on the condition of satisfying the requirement of comfortable indoor environment and indoor air quality. Therefore, it is critical to monitor and manage the air-conditioning system and to ensure the system operate in best condition.

HVAC system in modern buildings can represent a prototypical cyber-physical system with deeply coupled embedded sensing and networked information processing and interaction with physical environment. Modeling a building as a cyber-physical system (CPS) will play a vital role in achieving and operating zero net energy buildings [15].

CPS-based hybrid temperature control system (HTC) in smart home is concerned with sensing and timely control the multiple actuators to maintain a desired temperature with the optimized cost through the communication network. The indoor temperature fluctuated by internal and external heat loads are always sensed by the sensors. With the closed-loop interactions, the indoor temperature is feedback to the controller. Then, the controller with the decision-making algorithm decides the control actions which is send to actuators or device controller via the communication network to change the state of the physical world and to satisfy the specified goal.

In this chapter, some background knowledge related to this dissertation are conveyed to help the readers to get an overview on what is the smart houses, traditional temperature control system versus CPS-based temperature control system, PID controller and optimization problems in temperature control system.

2.2 Smart Homes

A smart home is a home assembled with home automation system. In smart home, the occupant can remotely control or program the automated home electronic devices by entering a signal command. For example, an occupant on vacation can use a Touchtone phone to provide a home security system, control temperature measures, switch appliances on or off, control lighting, program a home theatre or entertainment system and perform many other tasks [105].

A home automation system integrates electrical devices in a house with each other. Devices may be connected through a computer network to allow control by a personal computer, and may allow remote access from the internet. Through the integration of information technologies with the home environment, systems and appliances are able to communicate in an integrated manner which results in convenience, energy efficiency and safety benefits.

Automation in a smart environment can be viewed as a cycle of perceiving the state of the environment, reasoning about the state together with task goals and outcomes of possible actions, and acting upon the environment to change the state. Sensors monitor the environment using physical components and make information available through the communication layer. The database stores this information while other information components process the raw information into more useful knowledge (e.g, action models, and patterns). New information is presented to the decision-making algorithm upon request or by prior arrangement. The decision action is communicated to the service layers (information and communication) which record the action and communicate it to the physical components. The physical layer performs the action with the help of actuators or device controllers, thus changing the state of the world and triggering a new perception [22].

Home automation may include centralized control of lighting, HVAC, appliances, security locks of gates and doors and other systems, to provide improved convenience, comfort, energy efficiency and security. Home automation for the elderly and disabled can provide increased quality of life for persons who might otherwise require caregivers or institutional care [24].

Home automation has become popular in recent years due to the accessibility through the portable devices such as smartphone and tablet connectivity. The concept of the “Internet of Things ”is closely attached with the popularization of home automation. Other automated tasks may include setting the HVAC to an energy saving setting when the house is unoccupied and restoring the normal setting when the occupant is about to return.

HVAC solutions can include temperature and humidity control and more commonly fresh air, heating and natural cooling. Nowadays, home automation are varied as an internet-controlled by allowing the user to control the building’s heating and air conditioning systems remotely, or it could be linked to windows to allow automated opening and closing to allow hot air out and cool air in to allow for cooling of the thermal mass of the house structure. Many systems are designed to not only provide convenience but to also for better energy efficiency.

2.3 Traditional Temperature Control System versus CPS-based Temperature Control System

Controlling the temperature of building with HVAC systems have been studied extensively in the last decades. The basic function of a heating or air-conditioning system is to maintain comfortable conditions within a space for a specified period of time. Many researches have been proposed an efficient ways of control strategies to improve building process automation. The following summarizes the different types of temperature control system.

1. ***ON/OFF Control:*** The simplest type of temperature control used in the buildings is ON/OFF control. In this control, if the sensed temperature is below the set-point, then the heating system is fully ON. If the sensed temperature rises above the set-point, then the heating system is OFF. By this way, the temperature and

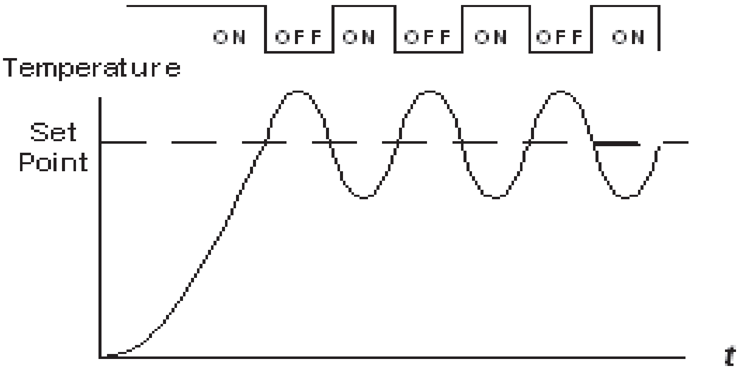


Figure 2.1: On/Off temperature control.

the output heat are controlled by ON/OFF controller. In practice this type of control can cause the heating system rapidly switches ON/OFF leading to inefficient system operation and increased mechanical wear.

2. ***Basic Temperature Control:*** In a basic room temperature control system, a sensor (thermostat) senses the room temperature and send it to the controller. The sensing data is usually passed in the form of an electricity voltage, where the voltage magnitude is proportional to the temperature. Then the controller compares this temperature to a set-point (desired) temperature and generates an error value. Depending on the magnitude of the error, the controller adjusts the output of the heating system up or down.

   In practice, this will involve operation of mechanical components such as a valve to increase or decrease the flow of hot water through a heating coil or radiator. Controllable components such as valves, pumps, fans and dampers are called as actuators. Therefore the output heat value from the controller is as a function of the error temperature. This type of control mechanism is commonly called feedback control, where the controlled variable (temperature) is fed back to the control system.

3. ***Proportional (P) Controller:*** This is a more advanced control algorithm, where the control action is proportional to the size of the error. In this control, if the temperature is below the set-point then the heating is ON and the output is proportional to the difference between the sensed temperature and the desired temperature; error

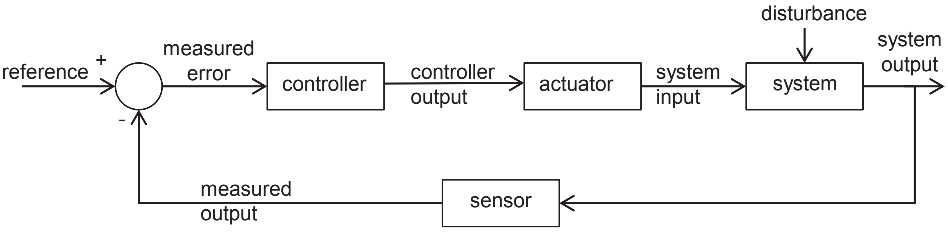


Figure 2.2: Feedback temperature control system.

temperature. If the temperature is above the set-point then the heating is OFF. If the error temperature gets small, so the heat output of the system is reduced. In practice, the operation of P controller is often limited as the output of the heating system is limited (i.e., it has maximum capacity). This is achieved by introducing a ‘proportional band’or ‘throttling range’—this is similar to a dead band in that a single set-point is replaced by an upper and lower limit.

As with ON/OFF control, proportional control is not a perfect mechanism because the throttling range affects the operation of the system:

- A narrow throttling range gives close control (a small error) at the expense of the system switching ON/OFF frequently, and
- A wide throttling range reduces the ON/OFF switching off the system (cycling) at the expense of poorer control.

It is impossible to completely eliminate the error between the desired temperature and the sensed temperature using only proportional control. There is always an offset error, where the controlled temperature never quite reaches the desired temperature.

4. ***PID Controller:*** PID controller incorporated a mix of proportional, integral and derivative control action. In this control, the output is a function of the size of the error $e(t)$, the rate of change of the error with time $T_d\frac{de(t)}{dt}$ and the integral of the error over time $\frac{1}{T_i}\int_0^t e(t)\,dt$. Where T_d is the derivation action time and T_i is the integral action time. PID control offers close control in that the control action responds to the rate of change of the error, while the integral control acts to eliminate the set-point error experienced with proportional control.

5. ***Modern Control Techniques:*** Some of the modern control techniques to enhance the quality of building indoor environments can be found in [25], [26], [27], [28] and [29]. [25] proposed a model-based feedback control strategy for indoor temperature regulation in buildings equipped with underfloor air distribution. The authors consider feedback regulation to optimize system operation based on WSN measurements. [26] proposed a model-based design of an embedded controller for building heating system to regulate suitably the indoor temperature in the room. [27] investigate a model-based Linear Quadratic Gaussian (LQG) control design for integrated building systems by using the Linear Quadratic Regulator (LQR) to minimize a performance criterion based on comfort and energy, and a Kalman Filter (KF) to estimate the state of the system. [28] introduced a platform based on model-driven hierarchical hybrid automata for modeling and simulation of building operation systems. [29] presented a model based hierarchical control strategy that balances comfort and energy consumption. At the lower level, each thermal zone is controlled by a PID controller while a model-based optimal control (e.g. LQR) is used at the higher level for a group of thermal zones. It means that the current desired temperature for each thermal zone (set by the building occupant) and the current temperature of each thermal zone are passed as inputs to the high level optimal controller which solves an optimization problem to compute the new set-points for the lower level PID controllers.

6. ***CPS-based:*** Unlike the traditional temperature control system, CPS-based temperature control system in smart homes is concerned with the sensing and control of temperature variation via the communication network. Such kind of system has a tight integration of sensing, computation, and actuation with multiple physical domains, e.g. iHouse, in which a sensor network with a variety of sensors is implemented in the buildings which measure electric power flow, temperature, relative humidity, etc. The energy management and temperature control system use the sensor measurements and determines actuation. For example, in case of rising the temperature because of the disturbance effect, the temperature sensors will transmit related data immediately/timely to the controller via wireless or wired communication. After receiving the feedback data from the sensors, the controller will make a decision

and takes the actuation dynamically; whether to increase the heating/cooling load. So that the user can take advantage to reduce the thermal discomfort in real time as much as possible. Or the controller can adjust the setting temperature (higher or lower) than normal setting if the controller got the information of the status of the occupants (absent/present) in the controlled room. The characteristics of CPS-based temperature control system have (i) discrete computation, (ii) deal with continuous quantities, (iii) concurrent, and (iv) run forever.

Therefore, users can benefit greatly from CPS-based temperature control system in homes such as reducing life-cycle building costs, improving thermal comfort and indoor air quality and conserving the energy. The overview of CPS-based temperature control system considered in this dissertation is expressed in Figure 3.1, Chapter 3.

2.4 PID Controller in HVAC System

PID controller consists of proportional, integral and derivative elements, is widely used in feedback control processes. Many researches have been conducted extensively PID control for HVAC system. Bi et al. [30] mention that 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. Moreover PID controllers have advantages such as disturbance rejection and zero steady state offset, and it have been commonly used in many HVAC applications.

The standard PID control configuration is shown in Figure 2.4 and we can express the PID algorithm as follows:

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de}{dt} \tag{2.1}$$

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 this configuration, the control signal $u(t)$ is the sum of the three terms. Each of these terms is a function of the tracking error $e(t)$. In [31], PID controller performs especially well when the system has first order dynamics (a single pole). Actually, in this case the P controller is a state-feedback control. In general, for the system with first-order dynamics the PI control is sufficient, and the D is not needed. PID controller, of course, is not the end-all of controllers. Sometimes, the controller just won't work very well. The following are cases when PID control doesn't perform well.

- Tight control of higher order process
- Systems with long delay times. In this case, the derivative term is not helpful. A "Smith predictor"is often used in this case
- Systems with lightly damped oscillatory modes
- Systems with large uncertainties or variations
- Systems with harmonic disturbance
- Highly coupled multi-input, multi-output systems especially where coordination is important

In general, these require the use of more sophisticated methods of control. So, the researchers have applied some intelligent control to the HVAC system, for example [32] to [38], which is used methods such as fuzzy control, neural network (NN), etc. [32] proposed a hybrid Cerebellar model articulation controller (CMAC)-PID control system, which combines the CMAC neural network and general PID control. Their controller has been shown that the feedback control by using traditional PID controller enhance the stability and reject the disturbance and the feed forward control by using CMAC neural network increase the response speed and control precision in HVAC system. [38] proposed a hybrid PID-cascade control system which combines the traditional PID control and cascade. Their simulation show that PID controller enhances the stability and rejects the disturbance and the cascade control and increases the response speed and control precision in the HVAC system.

In this dissertation the air-conditioner is designed with conventional PI controller which regulates the supply heating and cooling load based on the feedback error temperature.

Tuning the Parameters:

By tuning the parameters in the PID controller, the controller can deliver control action designed for specific control objectives. When designing a control system, we can

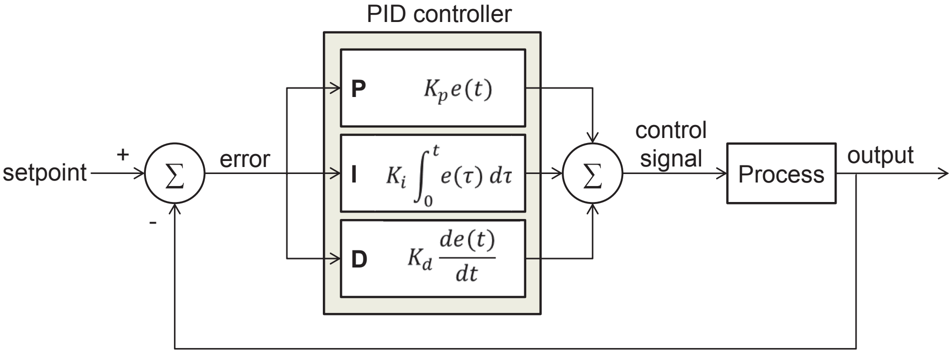


Figure 2.3: Typical PID controller.

observe how the system behaves by viewing the step response of the system. We can analysis the specific characteristics in a system from the step response of a system. These characteristics include but are not limited to: rise time, percentage overshoot, settling time, and steady state error. In order to figure out which parameters to tune, determining what characteristics of the system need improvement are important.

In this research, MATLAB/Simulink toolbox is used to adjust the parameters until the objectives are met. Then the parameters that give no overshoot than the maximum cooling load of actual air-conditioner of experiment house are chosen.

2.5 Supervisory Control

A control system involves four components: a system called the plant, the physical process that is to be controlled; the environment in which the plant operates; the sensors that measure some variables of the plant and the environment; and controller that determines the mode transition structure and selects the time-based inputs to the plant. The controller has two levels: the supervisory control that determines the mode transition structure, and the low-level control that determines the time-based inputs to the plant. Intuitively, the supervisory controller determines which of several strategies should be followed, and the low-level controller implements the selected strategy. Hybrid systems are ideal for modeling such tow-level controllers [1].

The scheme of supervisory control strategy considered in this thesis is shown in Figure 2.5 and represents a certain class of hybrid control systems. The supervisor S decides which of the controllers $C1, \ldots, Cm$ that should be active at each time instant. The

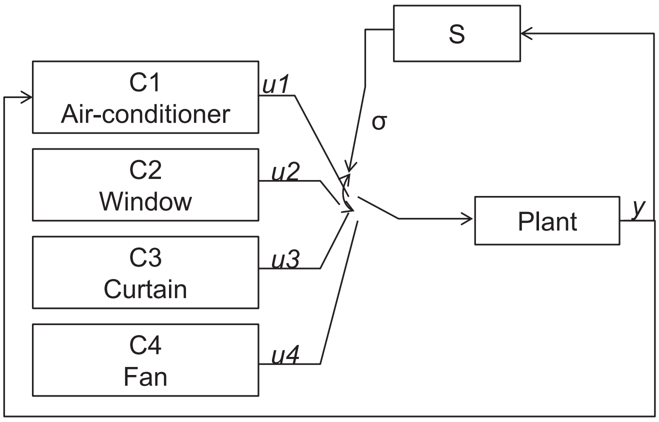


Figure 2.4: Supervisory control.

supervisory outputs a series of switching signals $\sigma : (0, \infty] \longrightarrow 1, \cdots, m$ and they are determined by computing the predefined algorithm in the supervisory with the input parameters of feedback measured data and environment data. In this thesis, the controllers are considered as the different types of actuators such as air-conditioner, window, fan and curtain. The main problem of supervisory (switching control) is chattering, i.e., very fast switching [39].

2.6 Optimization Problems in Home Temperature Control System

Good control is vital to get the acceptable performance in terms of comfort and energy efficiency. Inappropriate control parameters leads to a poorly configured control system, which in turn may give rise to uncomfortable conditions, energy waste and a reduction in the lifetime of system components. It is important that a building's control system is well designed, commissioned and maintained. However, it is not easy task to control the temperature efficiently because the thermal loads operated at HVAC system are time varying and depend on environment factors like outside weather conditions , and the number of people in the building.

Several studies have been conducted to optimize the temperature regulation system for the residential applications with different aspects such as the components of air-conditioner system, the whole picture of air-conditioning system.

The studies of optimization of the components/controlled parameters of air-conditioning system can be found in [40], [41] and [42]. For example, [40] used a conventional PI algorithm which controls the refrigeration load to reduce the variation of indoor temperature. In [41], the optimal control is applied to the actual central air-conditioning systems. [42] propose a multi-objective genetic algorithm to optimize the supervisory control strategy setpoints, such as supply air temperature, supply duct static pressure, chilled water supply temperature, minimum outdoor ventilation, zone supply air temperature, and zone air temperatures, of multizone HVAC system.

Lute et al. [43] attended to find cost-effective optimum supply heat to the building using a predictor for the indoor temperature, while maintaining a comfortable temperature in the building within a certain range of variation. Furthermore, the control of the temperature in the heating or cooling mode is kept between two predefined limits, instead of maintaining a process variable, as long as possible, constant at its setpoint.Optimization of residential temperature control in the presence of time-varying electricity price can be found in [44], [45]. [44] presented the incorporated optimization of model predictive and genetic algorithm for achieving an acceptable compromise between comfort and cost in the presence of time-varying electricity price.

Controlling of all home appliances for home energy management which is formulated as scheduling problem and is modelled as a mixed integer liner program is proposed in [45]. Recent researches on optimal control of HVAC components using model-based control techniques for achieving energy efficiency in buildings can be found in [44]to [49].

2.7 Thermal Comfort

Thermal comfort is that condition of mind that expresses satisfaction with the thermal environment [50]. A thermally comfortable home environment makes for occupant health and comfort. Control system based on thermal comfort can much more significantly improve building energy efficiency than ones maintaining one or more of thermal factors like air temperature, humidity, and air velocity at constant levels. Improving thermal comfort and designing its control system have become an important concern.

A. Predictive Mean Vote (PMV)

In this thesis, PMV index, which is proposed by Fanger [51], is used to evaluate thermal

comfort level. It is now most widely used index and adopted by ISO standard [52]. The PMV predicts the mean value of the votes of a large group of persons on the 7-point thermal sensation scale as listed below, based on the heat balance of the human body. Thermal balance is obtained when the internal heat production in the body is equal to the loss of heat to the environment [52].
+3 Hot
+2 Warm
+1 Slightly warm
+0 Neutral
-1 Slightly cool
-2 Cool
-3 Cold
The value of PMV can be calculated for different combinations of six primary factors, which affecting the thermal comfort, as listed below. The equation for calculating PMV index can be found in Appendix A.

1. ***Metabolic Rate***

   Metabolism is the body motor, and the amount of energy released by the metabolism is dependent on the amount of muscular activity [53]. Normally, all muscle activity is converted to heat in the body, but during hard physical work this ration may drop to 75 %. If, for example, one went up a mountain, part of the energy used is stored in the body in the form of potential energy. Traditionally, metabolism is measured in Met ($1\ Met = 58.15W/m^2$ of the body surface). A normal adult has a surface area of $1.7m^2$, and a person in thermal comfort with an activity level of $1Met$ will thus have a heat loss of approximately $100W$. Our metabolism is at its lowest while we sleep ($0.8Met$) and at its highest during sports activities, where $10Met$ is frequently reached.

2. ***Clothing Insulation***

   Clothing reduces the body's heat loss. Therefore, clothings is classified according to its insulation value. The unit normally used for measuring clothing's insulation is the Clo unit, but the more technical unit $(m^2)°C/W$ is also seen frequently ($1Clo = 0.155(m^2)°C/W$). The Clo scale is designed so that a naked person has a *Clo* value of 0.0 and someone wearing a typical business suit has a *Clo* value of 1.0. The *Clo* value can be calculated if the persons dress and the *Clo* values for the individual garments are known, by simply adding the *Clo* values together.

3. ***Air Temperature***

   It is the value of air temperature for the place occupants stay in.

4. ***Mean Radiant Temperature***

   Mean Radiant Temperature of an environment is defined as that uniform temperature of an imaginary black enclosure which would result in the same heat loss by radiation from the person as the actual enclosure. The calculation for mean radiant temperature is based on the Equation 2.2.

$$\overline{T}_r^4 = \sum_{i=1}^{6} T_i^4 F_{p-i} \tag{2.2}$$

5. ***Air Speed***

   It is the value of air speed around the occupants.

6. ***Relative Humidity***

   It is defined as the ratio of the partial pressure of water vapour in air-water mixture to the saturated vapour pressure of water at a prescribed temperature for the room.

B. Predicted Percentage Dissatisfied (PPD)

The PMV index predicts the mean value of the thermal votes of a large group of people exposed on the same environment. But as there are large variations, both physiologically and psychologically, from person to person, it is difficult to satisfy everyone in a space [52]. The environmental conditions required for comfort are not the same for everyone. It is meaningful to be able to predict the number of people likely to feel uncomfortably warm or cold. The PPD is the index that establishes a quantitative prediction of the percentage of thermally dissatisfied people who feel too cool or too warm. With the PMV value determined, calculate the PPD using Equation 2.3.

$$PPD = 100 - 95 \cdot exp(-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2) \tag{2.3}$$

The relationship about PMV and PPD can be seen in Figure 2.6.

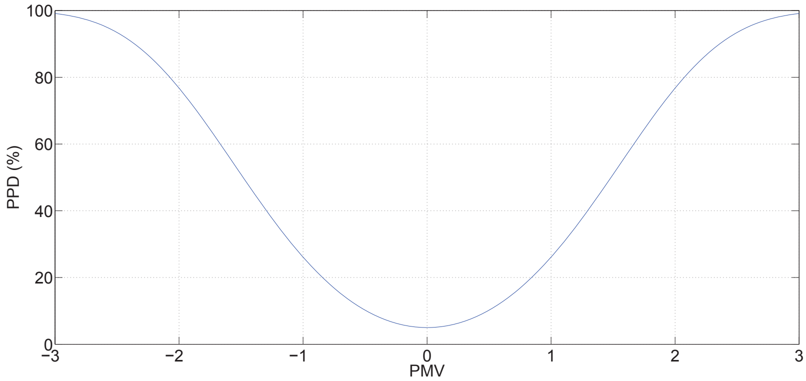


Figure 2.5: PMV-PPD.

C. Draught

The PMV and PPD express warm and cold discomfort for the body as a whole. But thermal dissatisfaction can also be caused by unwanted cooling or heating of one particular part of the body, which is known as local discomfort. The most common cause of local discomfort is draught. The discomfort due to draught may be expressed as the percentage of people predicted to be bothered by draught. We can calculate the draught rate (DR) using Equation 2.4.

$$DR = (34 - t_{a,l})(\overline{v}_{a,l} - 0.05)^{0.62}(0.37 \cdot \overline{v}_{a,l} \cdot T_u + 3.14) \qquad (2.4)$$

For $\overline{v}_{a,l} < 0.05 m/s$, use $\overline{v}_{a,l} = 0.05 m/s$, and for DR 100%, we use DR=100%. Symbol $t_{a,l}$ is the local air temperature in degree Celsius $20°C$ to $45°C$; $\overline{v}_{a,l}$ is the local mean air velocity in meters per second and its value is less than $0.5 m/s$; T_u is the local turbulence intensity in percent from 10% to 60%. The model applies to people at light, mainly sedentary activity with a thermal sensation for the whole body close to neutral and for prediction of draught at the neck.

Chapter 3

Design and Implementation of CPS-based Hybrid Temperature Control System

3.1 Introduction

HVAC system in modern buildings can represent a prototypical cyber-physical system with deeply coupled embedded sensing and networked information processing and interaction with physical environment. Modeling a building as cyber-physical system (CPS) will play a vital role in achieving and operating zero net energy buildings [15]. In recent years, the scientific community has begun to focus to apply the cyber-physical system in smart home [22] to reduce the energy consumption of the appliances intelligently in the house.

Intelligent buildings temperature control is a challenging automation problem because of the control of complex interconnected system. In this chapter, CPS-based hybrid temperature control (HTC) system which exhibits a tight integration of sensing, computation and actuation with physical domain is presented. It is composed with the sensor measurements, computation, determination and actuation. In this chapter, a conceptual framework for a CPS-based HTC system with multiple actuators is presented and the performance of the system is studied in terms of the room temperature regulation, energy consumption and thermal discomfort.

Actually, temperature control in home environment has been studied since many years ago. The difference of current research from the existing temperature control system is that many low cost temperature control actuators are considered by allowing the actuators to cooperate together to achieve the desired temperature with the minimum cost. In addition, HTC system in smart home environment is modeled as CPS[3]-based.

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 my viewpoint, these two controllers can be combined to control and monitor the temperature more efficient with 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, CPS-based HTC system can be extended not only control the temperature, but also control other comfort parameters, such as humidity, light, and so on.

Furthermore, it can dynamically keep the desired room temperature regardless of disturbance effect in physical system. To the best of my knowledge, there is no research has been conducted to propose the supervisory and PID controllers for temperature control with multiple actuators in the HVAC system. This becomes the motivation to study and investigate the proposed CPS-based HTC system in this chapter.

In this chapter, the detail of CPS-based HTC system with multiple actuators is explained. An actuator here is defined as an object that can potentially change the environment temperature through the thermal heat at the home, for instance, air-conditioner, window, fan, curtain, heater, etc.

This chapter covers the design and modeling of HTC system and its feedback control, the mathematical representation of the system, the heat equations of each actuator and the simulation studies of system performance in terms of room temperature regulation, energy consumption and thermal discomfort.

The rest of this chapter is organized as follows. In Section 3.2, the existing research works on HVAC system, the applications of CPSs in home environment and researches on efficient energy management in building structures are presented. Design and modeling of CPS-based HTC system is presented in Section 3.3. Thermal model of HTC system is explained in Section 3.4. In Section 3.5, HTC system with supervisory control is described.

Simulation studies in Section 3.6 are presented. In Section 3.7, a short discussion of the relation between the setting temperature and energy consumption is made and section 3.9 summarizes this chapter.

3.2 Related Works

The following section reviews the existing research 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 [25], [38], [32] and [26]. For example, Witrant et al [25] propose a model-based feedback control strategy for indoor temperature regulation in buildings equipped with underfloor air distribution. However, Homod et al. [38] 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. [32] 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 [26].

The relevant researches of CPS application for home environment system can be found in [54], [8], [11], [12] and [9]. Wang [54] 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. [8] propose the OSGi-based service architecture for cyber-physical home control system, which supports service-oriented control methods. Duchon, et al. [11] introduce an extension of existing software architecture tool, 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 two zones (rooms). Wan, et al. [6] reviews the existing research results in the area of CPS applications from the view points of energy management, network security, data transmission and management, model-based design, control techniques, and system resource allocation. The CPS applications in [6]include medical devices and systems, assisted living, traffic control and safety, advanced automotive systems, energy conservation, and smart structure.

Researches on efficient energy management in building structures can be found in [13], [14], [15] and [16]. [13] discuss Networked building control systems (such as HVAC and lighting) and it makes significantly improve energy efficiency and demand variability, reducing the dependence on fossil fuels and greenhouse gas emissions. [14] explores a conceptual framework of a cyber-physical system (CPS) for energy management in the residential and commercial buildings sector in US. [15] contributes 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 sqfeet office building as a closed system, they detail different strategies to reduce energy use from LEED certification to zero net energy use. [16] discuses CPS as an integral part of the SmartGrid: an ecosystem which will heavily rely in its basis on (real-time) information acquisition (monitoring), assessment and decision making as well as management (control) and the author indicate the vital role of CPS in SmartGrid.

A variety of approaches for controlling actuators in a cyber-physical system have been proposed in [56] and [57]. J. W. Branch et al. [58] proposed an auction-based method as a basic for distributed actuator coordination within their Sentire sensor and actuator networks. That studys primary goal was to coordinate actuators that were distributed in several places in a way that would facilitate the even allocation of energy resources. However, the desired temperature could not be achieved in several locations simultaneously. F. Xia et al. [59] proposed a GA-based two-stage fuzzy temperature control algorithm for industrial furnaces. According to their simulation results, the combination could reduce the number of fuzzy rules and keep the temperature around the set point, but only under the condition that we could grasp the characteristic of thermal conductivity. Furthermore, the cited study addresses neither fuel consumption fuel-efficiency performance. Fuzzy-based actuators controlling for minimizing power consumption in cyber-physical systems is proposed in [60]. Their simulation results reveal that fuzzy control method for actuators in a cyber-physical system can be used to minimize the power consumption of the system while accomplishing the desired set point.

In particular, there is only limited work in the CPS-based temperature control with multiple actuators in smart home environment. In contrast to existing CPS-based Smart Buildings, this chapter develops the application of CPS for smart home temperature control system with the multiple actuators. In this aspect, CPS-based home temperature control system with multiple actuators along with the supervisory control and PI controller is presented. The advantages of proposed system over a common home temperature control system is that the system is designed with interoperability among the four actuators along with the compromise between the user's preference and the energy cost.

3.3 Design and Modelling of CPS-based HTC System

This section presents the design and modelling of CPS-based hybrid temperature control (HTC) system with multiple actuators along with the supervisory controller and proportional and integral (PI) controller. In this dissertation, 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, fan, etc.

K. Wan et al. [61] pointed out that modelling and verification of CPS is complicated by their heterogeneous nature as well as their sheer complexity. A cyber-physical system can be modelled by either a structural/architectural specification, i.e., how their components: sensors, actuators and processors work; and how they are interconnected together) or behavioral specification, i.e., showing the response of each component to an internal or external event). Existing modelling techniques for cyber-physical system rely upon semantics to represent the relationship between the cyber and physical features of CPS, which is necessary for accurate modelling of any system. Generally speaking, mathematical formalisms for example, hybrid automata [62], process algebras [63] and description languages such as Labeled Hybrid Petri Nets [64] are popular candidates for modelling CPS.

The overview of system architecture for CPS-based temperature control system in smart home environment considered in this thesis is shown in Figure 3.1. The system is

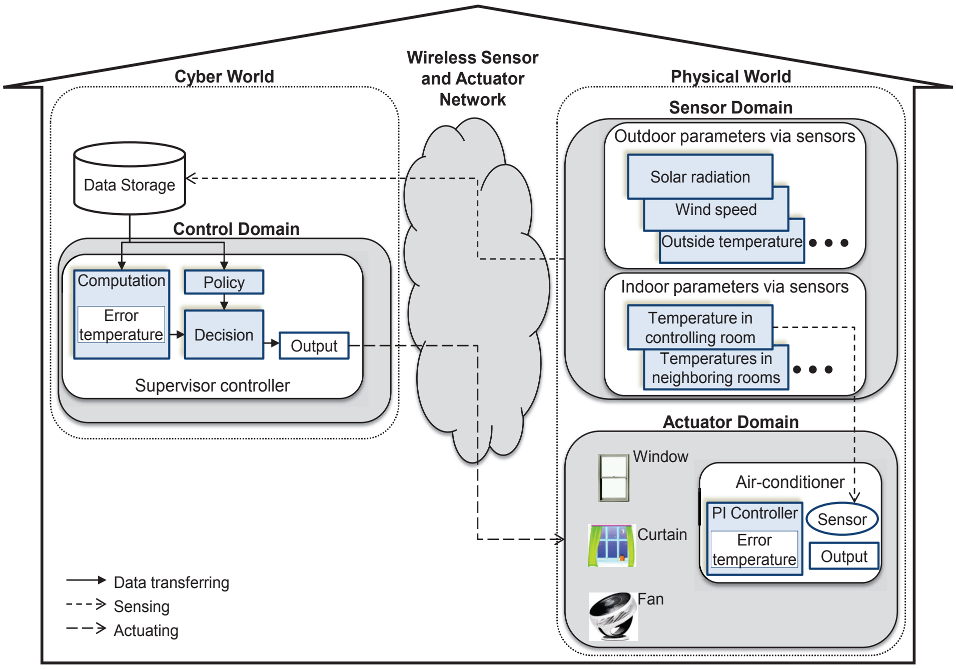


Figure 3.1: Overview of CPS-based HTC system.

defined as cyber world and physical world. Here, control domain is related to cyber world and sensor and actuator domains are concerned with the physical world. Wireless sensor and actuator network (WSAN) [65] is considered as the communication network of these two worlds. In sensor domain, two sets of sensors; outdoor environment sensors and indoor environment sensors; are included. Outdoor environment sensors sense the outdoor environment factors such as solar radiation, wind speed, outside temperature, etc. and indoor environment sensors sense the indoor parameters such as room temperature in controlling rooms and the neighbouring rooms. These sensors periodically transfer the sensing information to the controller in the control domain and to the data storage. The controller process the control algorithms by using all incoming feedback data and then make decisions on what actions should be performed upon the physical system. According to the control commands from the controller, the elements (e.g. as air-conditioner, window, fan, etc.) in the actuator domain of physical world performed actions (On/Off, Close/Open) to effect the desired changes. In this CPS-based HTC system, the air-conditioner is designed with proportional and integral (PI) controller which varies the supplied heating/cooling load based on the error temperature. Moreover, the actuators perform adaptively and cooperatively to accomplish the goal (to achieve the desired temperature). This feedback architecture of a cyber-physical control system is also called closed loop, implying that the cyber world and physical world are able to affect each other. The main idea of this feedback CPS-based system is to exploit measurements of the system's outputs and to determine the control demands that yield the desired system behaviour.

3.4 Mathematical Formulation for Thermal Model

The following section presents the mathematical representation of CPS-based HTC system and explains the heat equations that are applied in the room temperature calculation. A simplified controlled room of smart house is illustrated in Figure 3.2. The controlled room is equipped with one air-conditioner, curtain, fan and four windows mounted with automatic opened/close motor. The disturbances to such a house are usually the changing outdoor temperature, sun radiation through the window and human dissipation etc. In this thesis, outdoor temperature and human dissipation are considered as a disturbance example.

According to the energy conservation law, a simple mathematical model of building plant is represented as the rate of change of heat storage in the room is equal to the difference in heat going into the air-conditioned room and the heat going out of the air-conditioned room as expressed in Equation 3.1. As an example, the heat going into the air-conditioned room is the heat produced by equipment, persons in the room, conductive and solar heat gain, and the heat going out of the room is conductive heat transfer through the wall and heat gain through the air exchange.

$$C_i \frac{dT_i}{dt} = \sum Q_{in} - \sum Q_{out} \tag{3.1}$$

where C_i is the heat capacity coefficient of the room i, $Q_{in}(W)$ is the total heat gain in the room and $Q_{out}(W)$is the total heat loss from the room. T_i(°C) the temperature of the air in the room. Where $C_i = \rho_{air} V_{room} C_p$, ρ_{air} is air density (kg/m^3), V_{room} is room volume (m^3), and C_p is specific heat capacity air $(kJ/kg°C)$. In HTC system, the following kinds of heat transfer are considered and neglect the other internal heat gains such as the heat produced form the lightings, home appliances, etc.

1. Conductive heat transfer through the walls

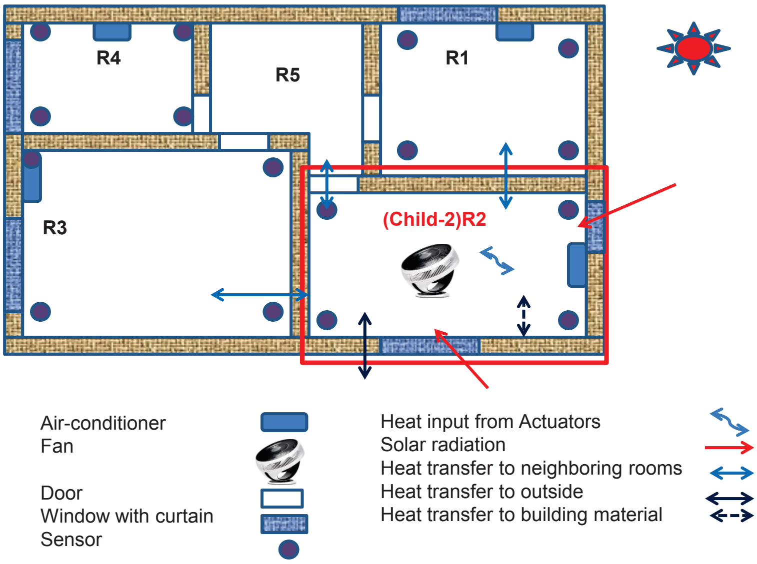


Figure 3.2: A sketch of building, it's interior and heat transfer.

2. Heat gain/loss due to the air exchange
3. Heat gain through the solar radiation
4. Heat produced from the occupants
5. Heat produced from the cooling and heating devices (e.g. air-conditioner, heater, fan, window)

Then, the equations for each kind of heat transfer are formulated.

1. Conductive heat transfer through the walls

Conductive heat transfer through the walls is modelled by a simple first order differential equation:

$$Q_{wal,i} = U_{w,i} A_{w,i} (T_j - T_{r,i}) \tag{3.2}$$

where $U_{w,i}$ is U value, overall heat transfer coefficient for walls of room i ($W/m^2\,°C$), $A_{w,i}$ is area of wall i, T_j the temperature at each side of the wall ($°C$).

2. Heat gain/loss due to the air exchange

Two types of mechanisms that contribute to the total air exchange are:

1. Infiltration: uncontrolled air flow through all the little cracks and openings in a building.
2. Ventilation: natural ventilation through open windows or doors and mechanical ventilation by fans.

The infiltration heat is given by

$$Q_{inf,i} = nVSpU_{w,i}A_{w,i}(T_j - T_{r,i}) \tag{3.3}$$

where $Q_{air,i}$ is infiltration heat loss (W) of room i, n is number of air changes per hour, V is room volume (m^3), T_{out} and $T_{r,i}$ are outside temperature and the inside temperature of room i. $Sp \cdot ht$ is specific heat factor for air and is calculated by $Sp \cdot ht$ factor=(specific heat capacity × 1000 to convert from kJ to Joules × density of air)/3600 to convert from hr seconds=(1·01×1000×1·2)/3600=0.34

3. Heat gain through the solar radiation

Two types of heat gain from the solar radiation; conductive and solar heat gains; are considered separately in this thesis. The following equations are also used for calculation of solar heat gain through the window with curtain and without curtain. Heat gain due to solar radiation through the glass is given by

$$Q_{ss,i} = q_{rad}A_{g,i}g_t \tag{3.4}$$

$qrad$ is measured solar radiation (W/m^2), $A_{g,i}$ is surface area of glass window (m^2) for room i, g_t is a fraction of the solar radiation combined with curtain and window (unit less). When the curtain is opened, $g_t = g_g$ which is solar energy transmittance for only glass. When the curtain is closed, g_t can be calculated by

$$g_t = g_g(1 - g_g \cdot \rho - \alpha \cdot \frac{u}{u+G}) \tag{3.5}$$

where G is thermal conductance of the air between glass and curtain ($W/m^2\ °C$), ρ is solar reflectance of the side of the curtain facing the incident radiation (unit less), and the value of α is calculated as

$$\alpha = 1 - \tau - \alpha \tag{3.6}$$

where τ is solar transmittance of the curtain, u is thermal transmittance of glass. Conductive heat gain through the glass due to the temperature difference between inside and outside is

$$Q_{dth,i} = A_g \cdot u_t(T_{out} - T_{r,i}) \tag{3.7}$$

where A_g is surface area of glass window (m^2), u_t is thermal transmittance for the system (combined with the curtain and window) ($W/m^2\ {}^\circ C$), T_{out} is outside temperature. When curtain opens, $u_t = u_g$ which is thermal transmittance for window only. When curtain is closed, u_t is calculated by

$$u_t = \frac{u_g}{1 + u_g \cdot \triangle R} \tag{3.8}$$

where $\triangle R$ is additional thermal resistance ($m^2\ {}^\circ C/W$)which can be calculated by

$$\triangle R = 0.55R + 0.11 \tag{3.9}$$

where R is thermal resistance for curtain.

4. Heat produced from occupants

Human beings release both sensible and latent heat to the conditioned space. Heat gain form occupant depends on the level of physical activity. The sensible and cooling load produced from occupant is given by

$$Q_{ocp,i} = N(SFG \cdot CLF + LGH) \tag{3.10}$$

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

5. Heat produced from the cooling and heating devices

In HTC temperature control system, four kinds of heating and cooling devices; air-conditioner, window, curtain and fan; that make the changes of inner heat load are considered.

5.1 Air-conditioner

For simplification, air condition (AC) system is considered as a unit, which removes energy from the room. In this paper the AC system is not modelled in detail, but presented as an energy input to the room model. Moreover, an air-conditioner is designed using a conventional PI controller and it controls the refrigeration (heating/cooling) loads based on the error temperature. Using MATLAB/Simulink toolbox, the gains of the PI controller are tuned and tested, and then choose the closet parameters to the practical values, i.e., the maximum cooling and heating load of real air-conditioner consider in this thesis.

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

$$Q_{ac} = 1.08CFM(T_a - T_{r,i}) \tag{3.11}$$

where CFM is air volume flow, T_{sa} is setting temperature of air-conditioner and $T_{r,i}$ is inside temperature of room i.

5.2 Window

Window is considered as one of the actuators since there is useful cooling and heating effect from opening window. This results in energy saving for HVAC system. In addition, natural ventilation helps to control the indoor air quality when the indoor is diluted with excess humidity, odours and contaminants. However, in warm or humid seasons, maintain the indoor temperature via natural ventilation may not be possible, so conventional air-conditioning systems are used as backups. In CPS-based HTC system, window opening and closing conditions is defined according to the outdoor environment factors such as outside temperature, solar radiation and raining status. Then, the heat generation to the space from outside to inside by the natural ventilation is given by

$$Q_{wd} = V_{airflow} C_p \rho_{air} (T_{so} - T_r) \tag{3.12}$$

$$V_{airflow} = A_{op} c_d v_{air} \tag{3.13}$$

where T_{so} is supplied outside temperature ($^{\circ}C$), $V_{airflow}$ is airflow rate through ventilation inlet opening, A_{op} is surface area of window opening (m^2), c_d is effectiveness of air, v_{air} is air velocity leaving the opening (m/s).

5.3 Curtain

The room with the curtain maintains the room temperature and it reduces the usage of air-conditioner/heater as well. Since the curtain retain heat during the winter and reject heat in the summer, resulting in lower cooling and heating loads. During the hot days of summer weather, closing the curtain before the sun shines directly onto the windows, the heat from the sun is blocked before it enters and warms the air. It will help to keep the room comfortable and lessen the need for air-conditioning. During the days of cold weather the curtain is opened if the window is receiving sunlight. 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 facts such as those explained above, the curtain is considered as one of the actuators in this temperature control system. The heat gain through the glass window with curtain and without curtain can be expressed as

$$Q_{cu} = Q_{ss} + Q_{dth} \tag{3.14}$$

where the values of Q_{ss} and Q_{dth} can be calculated as explained from Equation 3.4 to Equation 3.9.

5.4 Fan

Fan can be used in conjunction with air-conditioner to help reduce energy costs. Fan can help us more comfortable in our home during both summer and winter. Ceiling fans in themselves do not heat or cool a room, but the ceiling fan rotation allows improved air circulation, which can greatly improve the comfort of our living space. During the dry season, the fan is the best choice to cool the room and people might have to sue the fan all day long. However, the fan also can use when the rainy season and cold weather. During the cold season, the heat inside the room will rise up near the ceiling. Meanwhile, we can turn on the fan to push the heat through the walls and down toward the bottom of the room in order to get warm air. We can also use fan in the daytime with the window opening to get good air circulation in the room. This process makes the air movement in the room and it lets us to set the air conditioners setting temperature slightly higher while maintaining the same degree of comfort for occupants to save on energy.

Then, the heat gain/loss through the air exchange by using the fan can express as follows:

$$Q_{fa} = \frac{A_{fa} \times temperaturedifference(T_c - T_d)}{Rvalue} \tag{3.15}$$

where A_{fa} is surface area of heat transfer, roof area (m^2 or ft^2), T_c is the temperature of the ceiling, T_t is set-point temperature (desired temperature) and R is R value of roof or ceiling insulation ($m^2K.hr/W$).

Then, the heat dynamic for room i can be described as:

$$C_i \frac{dT_{r,i}}{dt} = \sum Q_{all} = Q_{wal,i} + Q_{inf,i} + Q_{ac_i} + Q_{wd,i} + Q_{cu,i} + Q_{fa,i} \tag{3.16}$$

3.5 CPS-based HTC System with Supervisory Control

In this section, the overview of HTC system with four actuators; air-conditioner, window, curtain and fan, and its feedback control is explained. CPS is an integration of physical dynamics and computational systems, so they commonly combine both discrete and continuous dynamics [1]. Therefore modelling of cyber and physical processes can be viewed as hybrid system modelling. For continuous dynamics, we can represent with differential equations and their corresponding actor models. For discrete dynamics, we can model by state machines (finite state automata). The temperature control system considered in this research is real-time system. This means that decisions are taken synchronized with information arrival which may be time-triggered or event-triggered.

Finite state machine (FSM) of hybrid temperature control system could be event triggered, in which case it will react whenever a (room and environment) temperature and other parameters (such as solar radiation, rain) inputs are provided. Alternatively, it could be time-triggered, meaning that it reacts at regular time intervals for some operation mode such as window opening/closing. It means that whenever window opening state starts, it transits to window closed state at regular time intervals.

The feedback control of CPS-based HTC system designed with the supervisory control and PI controller is illustrated in Figure3.3. In this thesis, the term HTC refers the whole temperature control system, and supervisory control is the main controller include in HTC system. The aim of the HTC system is to keep the room temperature within the upper and lower limits of desired temperature $T_{set}(t)$ and to control the operation of the actuators based on the decisions computed from the predefined algorithm to achieve that desired level. Here, the supervisory control is designed in such a way that accomplishing the control aims with the use of as less electricity as possible by energy consumed actuators and as much as possible the natural ventilation.

The controlled room temperature is regulated by the supervisory controller as a function

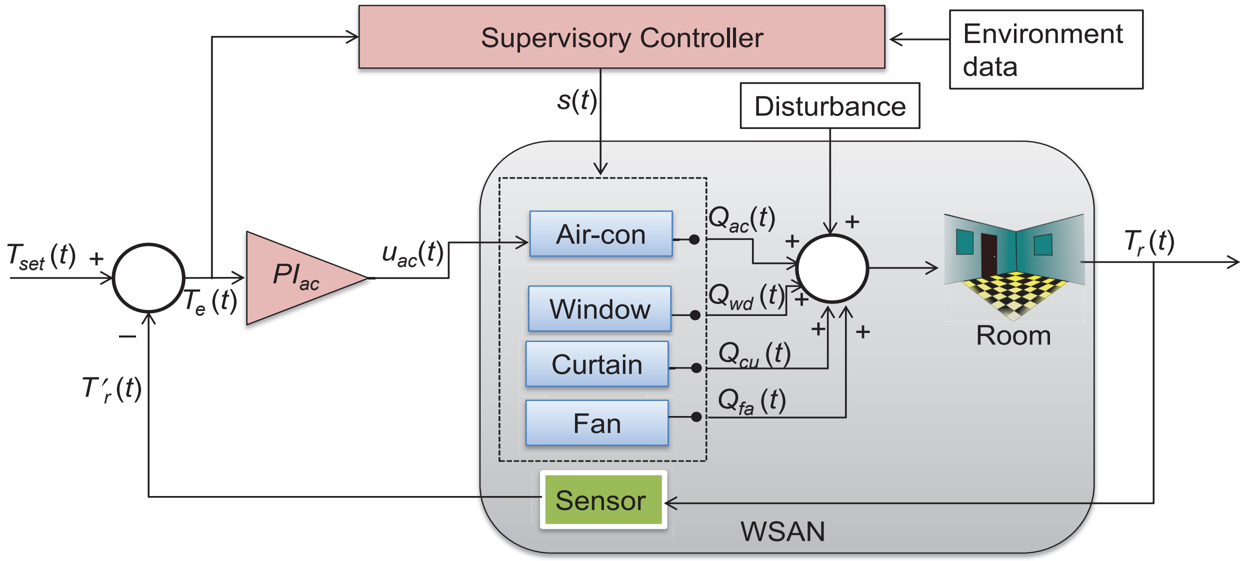


Figure 3.3: Block diagram of CPS-based HTC system.

of a reference (desired) temperature set by the occupant, the environment factors such as outside temperature, indoor air temperature, solar radiation, etc.

In HTC system, the room temperature $T_r(t)$ is continuously measured by the sensors installed in the room and these sensed data ($T_r'(t)$) are timely sent to the supervisory control and the PI controller installed in the air-conditioner. Then, the supervisory control computes the predefined control algorithm with the feedback data (error temperature $T_e(t)$) send by indoor environmental sensors and the data send by outdoor environmental sensors. Following this, the supervisory decides which action should be taken (i.e., deciding the control signal $s(t)$), e.g. window open or closed, air-conditioner on or off. In the case of the air-conditioner is triggered by the supervisory control, the PI controller computes the required control input value $u_{ac}(t)$ to the air-conditioner. In such a way, the supervisory control governing transitions between modes with the use of feedback real time input data in compromising with the predicted percentage of thermal discomfort (PPD) value and energy consumption is designed.

The operation modes and defined policies in supervisory control for HTC system with two actuators, three actuators and four actuators are explained detail in Section 3.7.

3.6 Simulation Studies

To evaluate the HTC system, the simulation are conducted with three parts. In the first simulation, the investigation of room temperature control with two actuators; air-conditioner and window is processed. In the second simulation, the affect of curtain in room temperature control and how the usage of curtain can reduce the usage of air-conditioner is investigated by considering the curtain as one of the actuators in HTC system. In the third simulation, the affect of room temperature is studied by adding one more actuator, fan, into the system. The simulations are conducted for both summer and autumn seasons.

3.6.1 Simulation Environment

In this section, the performance of CPS-based HTC system is analysed by conducting simulations with MATLAB/Simulink. In the simulation, the raw data from the experiments that were conducted at the smart home environment, iHouse, which is located at Nomi city, Ishikawa prefecture, Japan are used. The detail description of iHouse is available in Japanese version [21]. The measured outside temperature, the entered total heat from the sun through the windows of the bedroom on the second floor of iHouse during the typical summer seasons are used in simulation. This work was accomplished by the aid of home simulator presented in [16]. The two types of windows and curtains are mounted with automatic opened/close motor. In the bedroom, only one air-conditioner is available. The thermal comfort model is also implement in Simulink and equations for calculation the PMV and PPD values and the source codes are explained detail in Appendix.

This CPS-based HTC system, only an actuator air-conditioner is designed with PI controller. The air-conditioner using a conventional PI controller is considered and which ensures the desired temperature within the defined upper and lower levels. The gains for PI controller are obtained by tuning the values in Simulink control system toolbox. The sampling period of Simulink is 10 seconds. Table 3.1 summarizes the parameters, and values , their definition and units that are used in the following simulations.

Table 3.1: Parameters and settings

Parameter	*Definition*	*Value*
V_{room}	room volume	$5.005m \times 4.095m \times 3m$
ρ_{air}	air density	$1.2\ kg/m^3$
C_p	specific heat capacity air	$1.005\ kJ/kg°C$
T_d	desired temperature	$27°C$
T_{sa}	setting temperature of air-conditioner	$27°C$
COP	coefficient of performance	4.7
A_{g1} for type 1(L × W)	area of window type 1	$1.2 \times 1.77m$
A_{g2} for type 2(L × W)	area of window type 2	$1.2 \times 0.6m$
A_{op1} for type 1	opening area of window type 1	$2.124m^2$
A_{op2} for type 2	opening area of window type 2	$0.72m^2$
u_g	u value for glass	$5.6\ W/(m^2)°C$
c_d	effectiveness of air	0.61
SHG	sensible heat gain	$230\ Btu/h$
LHG	latent heat gain	$190\ Btu/h$
CLF	cooling load factor	1
	number of air-conditioner	1
	maximum cooling load	$5kW$

3.6.2 Room Temperature Control with Two Actuators

This section presents the room temperature control with two actuators; air-conditioner and window. Each actuator has the discrete-valued control inputs of ON/OFF. The hybrid temperature control (HTC) system presented in this section is organized in a set of 4 operation modes: $S_{(aoff,wcl)}$,$S_{(aoff,wop)}$, $S_{(aon,wcl)}$,$S_{(aon,wop)}$. Here, $S_{(aon,wop)}$, air-conditioner ON and window OPEN mode is defined as an unsafe mode, i.e., the modes that are not allowed to visit from other modes. In HTC system, the room temperature is controlled by supervisory which computes the appropriate switching signal based on the predefined algorithm with the parameters of feedback data and the other environment factors (see Figure 3.3). The input parameters to the supervisory are the feedback room temperature, the environment factors such as outside temperature, solar heat gain through the glass, raining status, and the switching signal is the continuous output. The performance requirement is to keep the temperature as close as possible to the desired temperature and minimize the electricity consumption as much as possible. It is also required to minimize the wear and tear of the actuators caused by switching. For example, in this HTC system, setting the parameter of timer $time_{wd}$; the state holding time of window opening to avoid an undesirably large frequency of switching between the mode $m1$ and the mode $m2$ in defining transition condition $\delta 12$.

Hybrid automaton describing the room temperature control system with two continuously control inputs can be represented as follows:
The set of discrete states variables
Q=$\{q_i\}$=$\{q_1, q_2, q_3, q_4\}$=$\{ON_{a1}, OFF_{a1}, ON_{a2}, OFF_{a2}\}$
Where a_i is type of the actuator and i=1,2 for the system presented in this section.

Then, the state composition of the room temperature control system $States_R$ is given by
$States_R$=$\{(OFF_{a1} \times OFF_{a2}), (OFF_{a1} \times ON_{a2}), (ON_{a1} \times OFF_{a2})\}$=$\{m_0, m_1, m_2\}$
=$\{S_{aoff,wcl}, S_{aoff,wop}, S_{aon,wcl}\}$
The set of continuous state variables $X = x = T_r = roomtemperature$
The set of continuous inputs V=$\{T_r^{'}, T_{out}, Q_{seast}, Q_{ssouth}, R_{ra}\}$
=$\{feedbackroomtemperature, outsidetemperature, solargainfromeast,$
$solargainfromsouth, raininglevel\}$

The set of continuous output variables Y= $\{s_i\}$=*control signals*=0,1,2. Control signal 0 means that the system is in the status of $S_{aoff,wcl}$ state, 1 means in $S_{aff,wop}$ and 2 means $S_{aon,wcl}$ status respectively.

The set of discrete transitions $E \subseteq Q \times Q$ and the set of guards $G : E \to P(X)$ associated with each transition $\delta = (q, q^{'}) \in E$ is explained detail in Table 3.5. The transition from state q to state $q^{'}$ is expressed using the symbol δ_{ij} for i,j=0,1,2,$i \neq j$ and the guard $g(q, q^{'})$ with the symbol of c_i. The differential equations govern the changes of the room temperature in the refinements of each state is expressed in Table 3.4. In the case the room temperature is not controlled, the indoor temperature refers to the temperature effected by the environment. Note that the symbols of state combination is used to express the state transition. The defined conditions of mode transitions in Table 3.2 and the parameter and settings for mode transition in Table 3.3 explained respectively.

Table 3.2: Defined conditions of mode transitions (Two actuators).

Guards	Definition
$c_1 = (T_{out} \leq 27°C)$ & $\&(Q_{sseast} == 0)\&$ $\&(Q_{sssouth} == 0)$	Outside temperature is less than $27°C$ and the heat gain from the solar radiation through the window glass from east and south position of the controlled room is zero
$c_2 = (R_{ra} == 0)$	No rain condition
$c_3 = (T_r \geq T_d + T_{thh})$	Controlled room temperature is greater than the desired temperature plus its upper limit value
$c_4 = (T_r \leq T_d + T_{thl})$	Controlled room temperature is less than the desired temperature plus its lower limit value

3.6.3 Simulation Setup (Two actuators)

To evaluate the HTC system, simulations are conduct with three cases. First simulation is to investigate how the room temperature is controlled by HTC system without the supervisory control. In this simulation, only one actuator (air-conditioner or window) is operated in one time to control the room temperature. Second simulation is concerned with the supervisory control in which the room temperature is controlled by the air-conditioner and window cooperatively according to the predefined algorithm. Here, the supervisory control is categorized in two types; supervisory control with timer-based and supervisory control without timer-based. Timer means that the state holding time of

Table 3.3: Parameters and settings.

Parameter	*Definition*	*Value*
T_d	Desired temperature	$27°C$
T_{thh}	Upper limit value of desired temperature	$+0.2°C$
T_{thl}	Lower limit value of desired temperature	$-0.2°C$
T_r	Controlled room temperature	
T_{out}	Outside temperature	Input file from the measured raw data
$Q_{ss-east}, Q_{ss-south}$	Heat gain from the solar radiation through the window glass from east and south position of the controlled room	Input file from the measured raw data
R_{ra}	The status of raining	Input file from the measured raw data
$Time_{wd}$	State holding time for window opening	30 minutes
$Time_{ac}$	State holding time for air-conditioning On	30 minutes
$Time_{ac2}$	The setting time to Off the air-conditioning once the room temperature arrives the upper limit of desired temperature	5 minutes

window opening mode, i.e., when the system transits to window opening mode, the system have to stay in it until the specific time is over. The purpose of using timer for state holding is to avoid the switching (chattering) problem. The state holding time of window opening mode is defined for 30 minutes. When the timer is over and the outdoor environment factors are still satisfy to open the window on that time, the system will keep staying at window opening mode until the second time timer is over again. Otherwise, the system will transit to air-conditioner ON mode when the timer is over and the outdoor environment factors do not satisfy the defined conditions at that moment.

Table 3.4: Symbol and definition of the modes and the differential equations govern the changes of room temperature in the refinement of each state (Two actuators).

Mode	Description	Rate of change of temperature
$m_0 = S_{aoff,wcl}$	Room temperature is controlled by any actuator	$\dot{T}_r(t) = \frac{1}{C_i}(Q_{wal}+Q_{inf}+Q_{dth}+Q_{ss}+Q_{ocp})$
$m_1 = S_{aoff,wop}$	Room temperature is controlled by only window	$\dot{T}_r(t) = \frac{1}{C_i}(Q_{wal}+Q_{inf}+Q_{dth}+Q_{ss}+Q_{ocp}+Q_{wd})$
$m_2 = S_{aon,wcl}$	Room temperature is controlled by only air-conditioner	$\dot{T}_r(t) = \frac{1}{C_i}(Q_{wal}+Q_{inf}+Q_{dth}+Q_{ss}+Q_{ocp}+Q_{ac})$

3.6.4 Simulation Results (Two actuators)

Simulation results obtained with/without supervisory control with timer-based/without timer-based are presented in this section. The focus during the simulation was on observing the improvements in terms of room temperature control, energy, thermal discomfort and the number of state transitions.

A. Room Temperature Regulation

The simulation results for one day conducted under the scenarios of supervisory control with timer-based/ without timer-based, and without supervisory control are presented in Figure 3.4. It can see that the settling time for achieving desired room temperature without supervisory control (only air-conditioner) is fastest among all other types of control, and supervisory control with timer-based gives faster setting time than without timer-based. It also observes that temperature control with only window opening could not achieve the desired temperature. However, it helps cooling down the room temperature for certain level in the morning and night time.

B. Thermal Discomfort

The simulation results of predicted percentage dissatisfied (PPD) values for one day in

Table 3.5: Transitions and their associated guards (Two actuators).

Transition	Transition condition (without timer)	Transition condition (with timer)
δ_{01}: mode $m0$ to mode $m1$	$c1\ \&\ \&\ c2\ \&\ \&\ not(c4)$	$c1\ \&\ \&\ c2\ \&\ \&\ not(c4)$
δ_{02}: mode $m0$ to mode $m2$	$not(c1)\ \&\ \&\ not(c4)\ \&\ \&\ c3$	$not(c1)\ \&\ \&\ not(c4)\ \&\ \&\ c3$
δ_{10}: mode $m1$ to mode $m0$	$c4$	$c4$
δ_{12}: mode $m1$ to mode $m2$	$not(c1)\ \&\ \&\ (c2 \Vert not(c2))\ \&\ \&\ not(c4)\ \&\ \&\ c3$	$(timer > Time_{wd})\ \&\ \&\ (not(c1) \Vert c1)\ \&\ \&\ not(c4)\ c3$
δ_{20}: mode $m2$ to mode $m0$	$c4$	$c4$
δ_{21}: mode $m2$ to mode $m1$	$c1\ \&\ \&\ c2\ \&\ \&\ not(c4)$	$-$

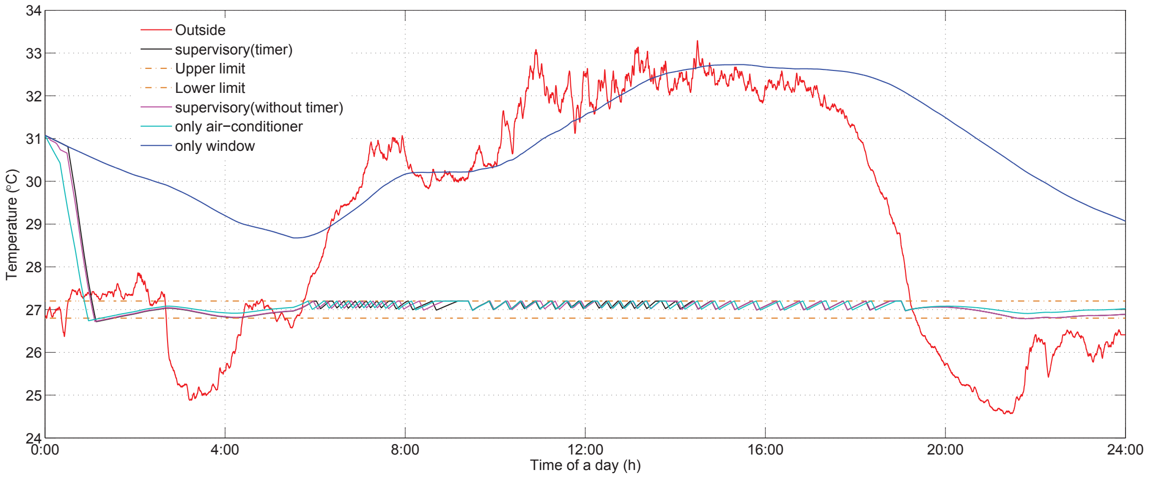


Figure 3.4: Room temperature variation.

controlled room is shown in Figure 3.5. In this simulation, the demand of the thermal comfort is fall in category C; the percentage of PPD is less than 15 (PPD(%) <15) and the range of PMV is between -0.7 and +0.7 (-0.7 ¡ PMV ¡ +0.7). The simulation results show that the PPD value is well controlled within the demand range by HTC system. It is seen that the demand PPD range with no supervisory control; the control of room temperature with air-conditioner only is achieved very fast. The settling time to demand

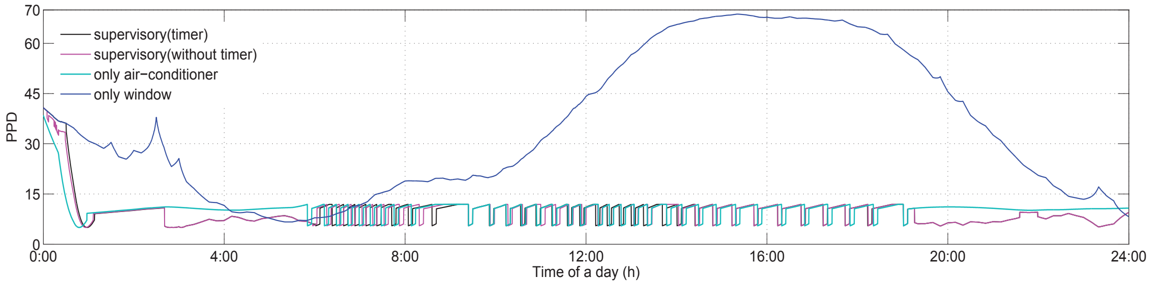


Figure 3.5: PPD.

PPD range with supervisory control with timer-based and without timer-based is not much different. Without supervisory control (only window) gives the demand PPD range for certain period, for example when the outside temperature falls to below $29°C$ in the figure of simulation results. Moreover, it observes that the values of PPD is not flatter much in the morning and evening where the room temperature is controlled with mode $m0$ and mode $m1$, and even the supervisory control without timer-based gives lower PPD value than the other two; supervisory control with timer-based and only air-conditioner control.

C. State Transitions

Figure 3.6 shows the status of operation states (modes) and the transition conditions between the operation modes. It can see that the system stays only in mode 2 $m2$: air-conditioner ON and window open mode; in day time because the environment factors defined in the controller do not satisfy to stay in mode $m1$. However, the system stays mostly in mode $m0$ and mode $m1$ in the morning and night time by keeping the PPD value within the demand range. It helps to reduce the operation time of air-conditioner and this leads to less electricity consumption. Moreover, it is seen that the switching problem; frequent switching between the mode $m0$ and mode $m1$: occurs with supervisory control without timer-based because of the rapid variation of outdoor environment factors, and it makes the system wired out. Therefore, supervisory control with timer-based is more preferable than without timer-based control from the view point of switching problem even it gives less energy consumption (see Figure 3.7).

D. Energy Comparison

Electricity consumption for three cases; without supervisory (only air-conditioner), with supervisory control with timer-based and without timer-based is shown in Figure3.7. It

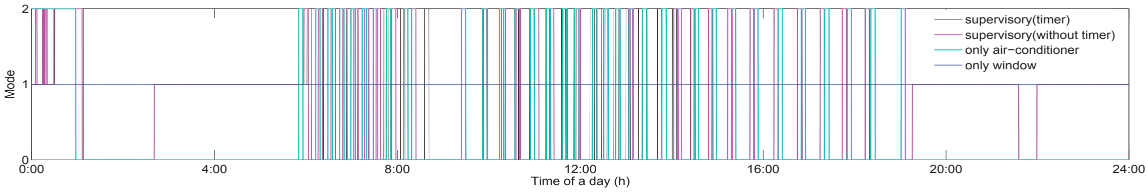


Figure 3.6: State transitions.

can be seen that the supervisory control with timer-based gives the lowest value among three types of control and supervisory with timer-based gives lower value than without supervisory control (only air-conditioner). It can observe that the energy consumption difference between without supervisory and supervisory control with timer-based is small. This is because the opening window could not help to reduce the room temperature in day time during summer season. In addition, the controller without supervisory also stays in mode $m0$ at night time. However, the electricity consumption could reduce when the HTC system with supervisory control is applied at night time, i.e., the system operates in mode $m0$ ($S_{aoff,wcl}$) and mode $m1$ ($S_{aoff,wop}$) only. It also observes that supervisory control with timer-based and without timer-based gives lower PPD value than without supervisory control.

The energy consumption (kWh) of air-conditioner is calculated as below

$$P(t) = \frac{\int Q_{aircon}(t)dt}{COP} \tag{3.17}$$

where Q_{aircon} is the cooling/heating load of air-conditioner (W) and COP is the coefficient of performance. COP is assumed as a constant value 4.7.

3.6.5 Room Temperature Control with Three Actuators

In this section, the modify CPS-based HTC system is presented by adding one more actuator; the curtain, along with the supervisory control which is designed in energy efficient way. Following this, the simulation results is showed in comparing with the results presented in Section (3.6.2.2) in terms of the energy consumption.

Moreover, the important role of the curtain to main the room temperature and to reduce the usage of the air-conditioner/heater is discussed as well. The mathematical

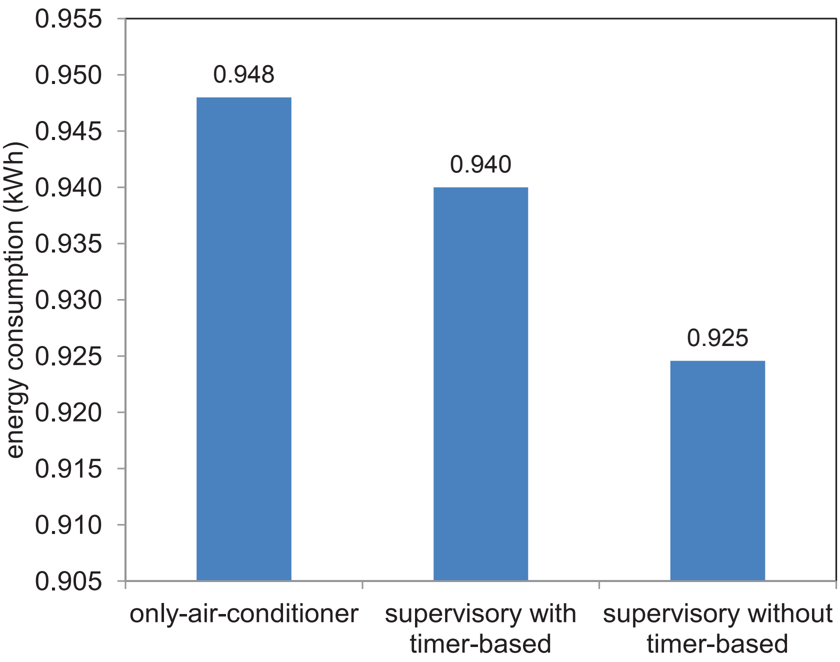


Figure 3.7: Comparison of energy consumption.

formulation of the heat through the window and curtain is presented in Section 3.4 and the same mathematical heat equations as explained in Section 3.4 is used. Same as the CPS-based HTC system with two actuators, five types of heat that makes the changes of room temperature are considered;

1. Conductive heat transfer through the walls
2. Heat gain /loss due to the air exchange
3. Heat gain through the solar radiation
4. Heat produced from the occupants
5. Heat produced from the cooling and heating devices (e.g. air-conditioner, heater, fan, window)

Heat gain from the curtain open/closeQ_{cu} can be calculated from the addition of Q_{ss} and Q_{dth} values. The original state composition of the system with three actuators is organized in a set of eight operation modes. However, we consider only five operation modes of $S_{aoff,wcl,ccl}$, $S_{aoff,wcl,cop}$,$S_{aoff,wop,cop}$,$S_{aon,wcl,ccl}$ are considered and define the modes of $S_{aoff,wop,ccl}$,$S_{on,wop,ccl}$,$S_{aon,wop,cop}$ as unsafe modes. The supervisory control computes the control signals based on the predefined algorithm with the feedback data and the other environment factors. The continuous inputs to the supervisory are the feedback room temperature, the environment factors such as outside temperature, solar heat gain through the glass, raining status, and the switching signal is the continuous output. The performance requirement is to keep the temperature as close as possible to the desired temperature and minimize the electricity consumption as much as possible. It is also required to minimize the wear and tear of the actuators caused by switching.

Supervisory Control with Hybrid Automaton

The hybrid automaton describing the room temperature control system can be represented as follows.

The set of discrete states variables

Q= $\{q_i\}$=$\{$ $q_1, q_2, q_3, q_4, q_5, q_6\}$=$\{ON_{a1}, OFF_{a1}, ON_{a2}, OFF_{a2}, ON_{a3}, OFF_{a3}\}$

Where a_i is the type of the actuator and i=1, 2, 3 for HTC system presented in this section.

Then, the state composition of the room temperature control system $States_R$ is given by $States_R$=$\{$ $(OFF_{a1} \times OFF_{a2} \times OFF_{a3})$, $(OFF_{a1} \times OFF_{a2} \times ON_{a3})$, $(OFF_{a1} \times ON_{a2} \times ON_{a3})$, $(ON_{a1} \times OFF_{a2} \times OFF_{a3})$, $(ON_{a1} \times OFF_{a2} \times ON_{a3})$ $\}$= $\{$ $m0, m1, m2, m3, m4$ $\}$= $\{S_{aoff,wcl,ccl}$, $S_{aoff,wcl,cop}$, $S_{aoff,wop,cop}$, $S_{aon,wcl,ccl}$, $S_{aon,wcl,cop}$ $\}$

The set of continuous state variables X=$\{x\}$=$\{T_r\}$=$\{roomtemperature\}$

The set of continuous inputs variables V=$\{T_r^{'}, T_{out}, Q_{seast}, Q_{ssouth}, R_{ra}\}$=$\{feedbackroomtemperature, ou$

The set of continuous output variables Y= $\{s_i\}$=$\{\textit{control signals}\}$=$\{0,1,2,3,4\}$

The set of discrete transitions $E \subseteq Q \times Q$ and the set of guards $G : E \rightarrow P(X)$ associated with each transition $\delta = (q, q^{'}) \in E$ is explained detail in Table 3.5. The transition from state q to state $q^{'}$ is expressed using the symbol δ_{ij} for i,j=0,1,2,$i \neq j$ and the guard $g(q, q^{'})$ with the symbol of c_i.

The meaning of the each operation mode and the differential equations govern the changes of room temperature in the refinement of each state is explained in Table 3.7. The defined conditions of mode transition and the parameters and settings shown in Table 3.2 and Table 3.3 are used in the simulation studies of this section as well. Note that the symbols of state combination is used to express the state transition.

Table 3.6: Transitions and their associated guards (Three actuators).

Transition	Transition condition
δ_{01}: mode $m0$ to mode $m1$	$c1$ & & $not(c2)$ & & $not(c4)$
δ_{03}: mode $m0$ to mode $m3$	$not(c1)$ & & $(not(c2) \parallel c2)$ & & $not(c4)$ & & $c3$
δ_{10}: mode $m1$ to mode $m0$	$c4$
δ_{12}: mode $m1$ to mode $m2$	$c1)$ & & $c2$ & & $not(c4)$ & & $c3$
δ_{13}: mode $m1$ to mode $m3$	$not(c1)$ & & $(not(c2) \parallel c2)$ & & $not(c4)$ & & $c3$
δ_{14}: mode $m1$ to mode $m4$	$c1$ $(not(c2) \parallel c2)$ & & $not(c4)$ & & $c3$
δ_{20}: mode $m2$ to mode $m0$	$(timer > Time_{wd})$ & & $not(c1)$ & & $(not(c2) \parallel c2)$ & & $not(c4)$ & & $c3$
δ_{23}: mode $m2$ to mode $m3$	$(timer > Time_{wd})$ & & $c1$ & & $(not(c2) \parallel c2)$ & & $not(c4)$ & & $c3$
δ_{24}: mode $m2$ to mode $m4$	$c4$
δ_{30}: mode $m3$ to mode $m0$	$c4$
δ_{32}: mode $m3$ to mode $m2$	$c1$ & & $c2$ & & $not(c4)$ & & $c3$
δ_{40}: mode $m4$ to mode $m0$	$c4$
δ_{42}: mode $m4$ to mode $m2$	$c1$ & & $c2$ & & $not(c4)$ & & $c3$
δ_{43}: mode $m4$ to mode $m3$	$not(c1)$ & & $(not(c2) \parallel c2)$ & & $not(c4)$ & & $c3$

3.6.6 Simulation Setup (Three actuators)

In this section, the simulations are conduct with two parts. In the first part, on the study of the affect of curtain in room temperature is focused and investigate how the usage of curtain can maintain the room temperature and reduce the usage of air-conditioner. This simulation is done only for summer season. In the second part, the curtain is added as an actuator in the system and study how the room temperature is controlled from the viewpoint of energy consumption in comparison with the room temperature control with two actuators, i.e., without curtain. In this simulation, the same parameters and setting for supervisory control with hybrid automaton as explained in Table 3.2 & Table 3.3 are used.

Table 3.7: Symbol and definition of the modes and the differential equations govern the changes of room temperature in the refinement of each state (Three actuators).

Mode	Description	Rate of change of temperature
$m_0 = S_{aoff,wcl,ccl}$	Room temperature is controlled by any actuator	$\dot{T}_r(t) = \frac{1}{C_i}(Q_{wal} + Q_{inf} + Q_{dth} + Q_{ss} + Q_{ocp})$
$m_1 = S_{aoff,wcl,cop}$	Room temperature is controlled by only curtain	$\dot{T}_r(t) = \frac{1}{C_i}(Q_{wal} + Q_{inf} + Q_{dth} + Q_{ss} + Q_{ocp})$
$m_2 = S_{aoff,wop,cop}$	Room temperature is controlled by window and curtain	$\dot{T}_r(t) = \frac{1}{C_i}(Q_{wal} + Q_{inf} + Q_{dth} + Q_{ss} + Q_{ocp} + Q_{wd})$
$m_3 = S_{aon,wcl,ccl}$	Room temperature is controlled by only air-conditioner	$\dot{T}_r(t) = \frac{1}{C_i}(Q_{wal} + Q_{inf} + Q_{dth} + Q_{ss} + Q_{ocp} + Q_{ac})$
$m_4 = S_{aon,wcl,cop}$	Room temperature is controlled by air-conditioner and curtain	$\dot{T}_r(t) = \frac{1}{C_i}(Q_{wal} + Q_{inf} + Q_{dth} + Q_{ss} + Q_{ocp} + Q_{ac})$

3.6.7 Simulation Results (Three actuators)

In this section, the simulation results on the study of affect of curtain in the room temperature control and the comparative study of room temperature control with two actuators and three actuators are presented from the energy consumption aspect.

A. Effect of Curtain on Heat Gain

Figure 3.8 and 3.9 show the simulation results of the affect of curtain in room temperature changes. Figure 3.8 (above Figure) shows the amount of heat gain from the solar radiation through the windows under the conditions of curtain open and curtain close. It observes that the amount of heat entering the room under the curtain open state is much higher than close state. It can see that the maximum difference value is around at noon

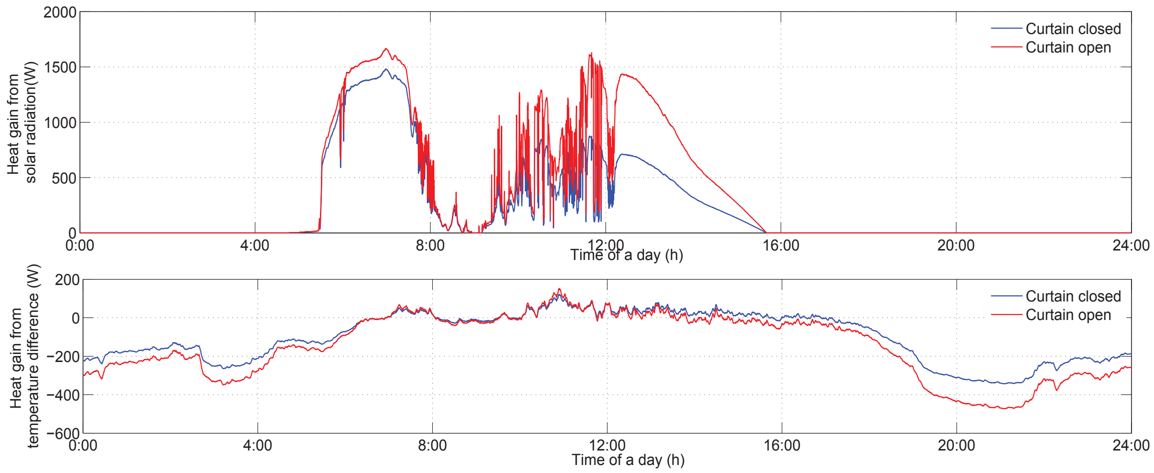


Figure 3.8: Heat gain from solar radiation (above) and heat gain from heat conduction; temperature difference(below).

time. By closing the curtain the amount of solar radiation is reduced $555.47W$ and the solar gain from temperature difference is $129.302\ W$.

Figure 3.8 (below) shows the simulation results of heat gain from temperature difference between inside and outside. It observes that the difference of heat gain between curtain open and closed conditions is relatively large when the inside and outside temperature difference is high. But when the temperature difference is small, the heat gain under two conditions is not obvious. As long as the outside temperature is low, the heat gain from the temperature difference is getting low. The results show that the value of heat gain with curtain closed is larger than curtain open state in the morning and night times. So it is preferable to open the curtain in the morning and night times.

B. Room Temperature Regulation

The simulation results for one day conducted under the scenario of supervisory control with and without curtain, and without supervisory control are shown in Figure 3.9. It can see that the settling time for achieving desired temperature without supervisory control (only air-conditioning) is the fastest amount all other types of control. The results also show that the room temperature is well controlled by HTC system under all types of controllers.

C. Thermal Discomfort

Figure 3.10 shows the simulation results of PPD values for one day in controlled room. As explained in Section 3.6, the demand of the thermal comfort is fall in category C;

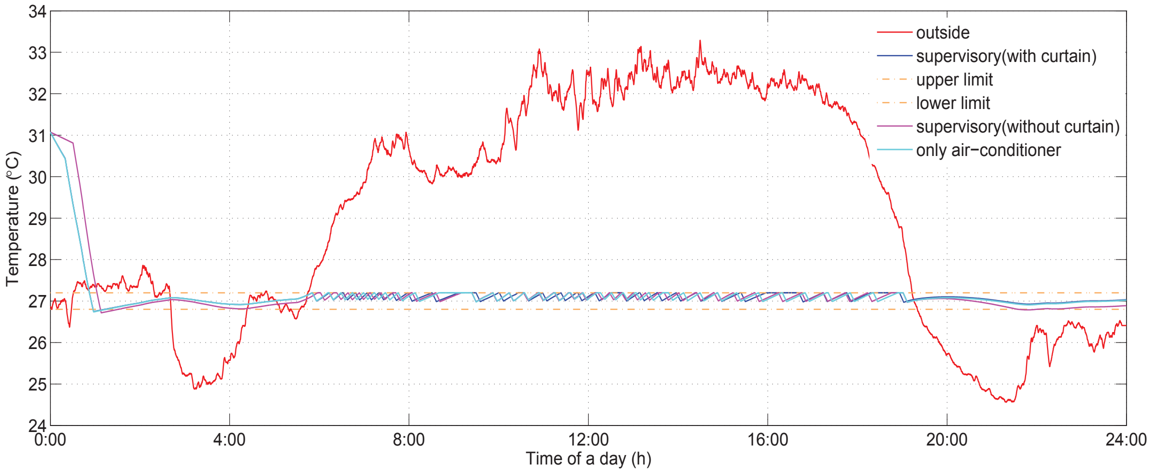


Figure 3.9: Room temperature variation.

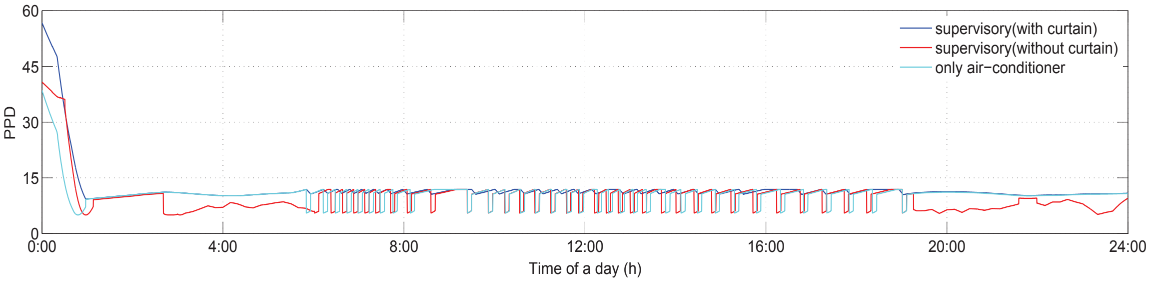


Figure 3.10: PPD.

the percentage of PPD is less than 15 (PPD(%) $<$ 15). It can see that PPD value is well controlled within the demand band. In the morning and at night time, supervisory control without curtain gives lower PPD value than supervisory control with curtain and without supervisory control (only air-conditioner). It means that it is more preferable to open the curtain on the summer days of morning and night times.

D. Energy Consumption

Figure 3.11 shows the energy consumption of air-conditioner for different scenarios. It observes that the energy consumption of air-conditioner without supervisory control (only air-conditioner) is the largest among the three scenarios and supervisory control with curtain gives lower power consumption than without curtain. Energy consumption is reduced to 13.4% by supervisory control with curtain in compare with without curtain.

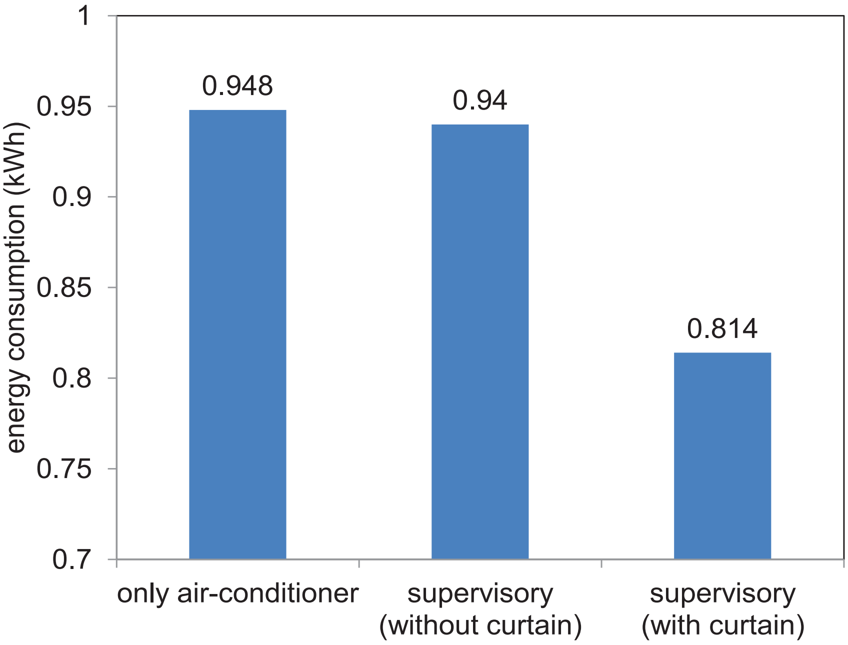


Figure 3.11: Comparison of energy consumption.

3.6.8 Temperature Control with Four Actuators

In this section, CPS-based HTC system with four actuators is presented by adding one more actuator; fan, in the existing system. The purpose of considering fan as one of the actuators in temperature control is explained in details in Section 3.4. In this system, fan is designed in such a way that it is operated only when the occupant is present in the room.

The system presented in this section is organized in a set of 16 operation modes:
$\{S_{aoff,foff,wcl,ccl}$, $S_{aoff,foff,wcl,cop}$, $S_{aoff,foff,wop,ccl}$, $S_{aoff,foff,wop,cop}$,
$S_{aoff,fon,wcl,ccl}$, $S_{aoff,fon,wcl,cop}$,$S_{aoff,fon,wop,ccl}$, $S_{aoff,fon,wop,cop}$,
$S_{aoff,foff,wcl,ccl}$, $S_{aon,foff,wcl,ccl}$, $S_{aon,foff,wcl,cop}$, $S_{aon,foff,wcl,cop}$,
$S_{aoff,fon,wop,ccl}$, $S_{aon,foff,wop,cop}$, $S_{aon,fon,wcl,ccl}$, $S_{aon,fon,wcl,cop}$,
$S_{aon,fon,wop,ccl}$, $S_{aoff,fon,wop,cop}\}$
And the operation modes of $\{$ $S_{aoff,foff,wop,ccl}$, $S_{aoff,fon,wop,ccl}$, $S_{aon,foff,wop,ccl}$, $S_{aon,foff,wop,cop}$, $S_{aon,fon,wop,ccl}$, $S_{aon,fon,wop,cop}$ $\}$

The supervisory control decides the series of switching signals by using the parameters of feedback data, presence of occupancy in the room and the environment factors along with the predefined algorithm in the controller. To investigate the nature of the system, the most possible 4 different types of supervisory controller are formulated. The algorithm implemented in controller is designed based on the general behaviour of the occupant and designer's knowledge. The only difference between the supervisory controllers is the operation mode considered in for the system operation. For example, in supervisory type 2, $SO2$, the operation modes $m3$ ($S_{aoff,fon,wcl,ccl}$) and modes $m4$ ($S_{aoff,fon,wcl,cop}$) are not considered. The details of operation modes, state transitions and defined guards for each controller are explained details in Table 3.8 to 3.11. The excluded operation modes; the modes that are not considered in supervisory control; for corresponding supervisory type are described as follows.

Table 3.8: Types of supervisory controllers.

Supervisory type	Excluded modes
SO1	-
SO2	mode $m3$, mode $m4$
SO3	mode $m3$, mode $m4$, mode $m5$
SO4	mode $m3$, mode $m4$, mode $m5$, mode $m8$, mode $m9$

The continuous inputs to the supervisory control are feedback room temperature, the environment factors such as outside temperature, solar heat gain through the glass, raining status, the presence of occupant and the switching signal is the continuous output.

Supervisory Control with Hybrid Automaton

The hybrid automaton describing the room temperature control system can be represented as follows.

The set of discrete states variables $Q= \{q_i\}=\{ q_1, q_2, q_3, q_4, q_5, q_6, q_7, q_8\}$
$=\{ON_{a1}, OFF_{a1}, ON_{a2}, OFF_{a2}, ON_{a3}, OFF_{a3}, ON_{a4}, OFF_{a4}\}$

Where a_i is the type of the actuator and i=1, 2, 3, 4 for HTC system presented in this section.

Then, the state composition of the room temperature control system $States_R$ is given by $States_R=\{$ $(OFF_{a1} \times OFF_{a2} \times OFF_{a3} \times OFF_{a4})$, $(OFF_{a1} \times OFF_{a2} \times OFF_{a3} \times ON_{a4})$, $(OFF_{a1} \times OFF_{a2} \times ON_{a3} \times ON_{a4})$, $(OFF_{a1} \times ON_{a2} \times OFF_{a3} \times OFF_{a4})$, $(OFF_{a1} \times ON_{a2} \times OFF_{a3} \times ON_{a4})$, $(OFF_{a1} \times ON_{a2} \times ON_{a3} \times ON_{a4})$, $(ON_{a1} \times OFF_{a2} \times OFF_{a3} \times OFF_{a4})$,

$(ON_{a1} \times OFF_{a2} \times OFF_{a3} \times ON_{a4})$, $(ON_{a1} \times ON_{a2} \times OFF_{a3} \times OFF_{a4})$, $(ON_{a1} \times ON_{a2} \times OFF_{a3} \times ON_{a4})$,}

={ $m0, m1, m2, m3, m4, m5, m6, m7, m8, m9$ }

={$S_{aoff,foff,wcl,ccl}$, $S_{aoff,foff,wcl,cop}$, $S_{aoff,foff,wop,cop}$,$S_{aoff,fon,wcl,ccl}$,$S_{aoff,fon,wcl,cop}$, $S_{aoff,fon,wop,cop}$, $S_{aon,foff,wcl,ccl}$, $S_{aon,foff,wcl,cop}$, $S_{aon,fon,wcl,ccl}$, $S_{aon,fon,wcl,cop}$ }

The set of continuous state variables X={x}={T_r}={$roomtemperature$}

The set of continuous inputs variables V={$T_r^{'}, T_{out}, Q_{seast}, Q_{ssouth}, R_{ra}$}

={$feedbackroomtemperature, outsidetemperature, solargainfromeast,$ $solargainfromsouth, raininglevel$}

The set of continuous output variables Y= {s_i}={*control signals*}={0,1,2,3,4,5,6,7,8,9}

The set of discrete transitions $E \subseteq Q \times Q$ and the set of guards $G : E \rightarrow P(X)$ associated with each transition $\delta = (q, q^{'}) \in E$ is explained detail in Table 3.5. The transition from state q to state $q^{'}$ is expressed using the symbol δ_{ij} for *i,j*=0,1,2,4,5,6,7,8,9, $i \neq j$ and the guard $g(q, q^{'})$ with the symbol of c_i.

The symbols and definition of the modes and differential equations govern the changes of the room temperature in the refinements of each state is expressed in Table 3.8. The defined conditions of mode transition and the parameters and settings shown in Table 3.2 and Table 3.3 are used in the simulation studies of this section as well. Note that the symbols of state combination are used to express the state transition.

3.6.9 Simulation Setup

In this section, the simulations for different 4 types of supervisory control are conducted to investigate the performance of room temperature regulation, thermal discomfort and energy consumption when the one more actuator, fan is added to the system. The difference between the supervisory types is that the defined operation modes are different for each type of supervisory. For example, in supervisory type 1, we consider all type of operation modes in the room temperature control except the unsafe modes. Mode $m3$ and mode $m4$ in supervisory type 2, mode $m3$, mode $m4$ and mode $m5$ in supervisory type 3, and mode $m3$, mode $m4$, mode $m5$, mode $m8$ and mode $m9$ in supervisory type 4 are excluded in room temperature controlling respectively.

3.6.10 Simulation Results

Simulation results of room temperature regulation, thermal comfort, and energy consumption of room temperature control by HTC system with four different types of supervisory control designed based on the presence of occupancy are presented.

A. Room Temperature Regulation

Figure3.12 (above) shows the simulation results of room temperature variation by CPS-based HTC system with different four types of supervisory control. It is seen that the initial settling of room temperature with supervisory type 1 ($SO1$) is the largest and supervisory type 3 ($SO3$) is the smallest among four supervisory types. However, the temperature seems a little higher than upper limit around 7:00 with the supervisory control ($SO1$), the PPD values still remains within the demand band. Therefore it can say that the system well controls the room temperature with all different four types of supervisory controllers.

B. Thermal Discomfort

The simulation results of PPD under the four different types of supervisory controls is shown in Figure 3.12 (below). It can see that $SO2$ and $SO3$ give the faster settling time to demand PPD band than the other two controllers and $SO1$ gives the largest settling time to reach the demand PPD band. It also observes that $SO3$ and $SO4$ give the lower PPD vales than the other two in the morning and night time.

C. Energy Consumption

Figure 3.13 shows the energy consumption of HTC system under the different four types of supervisory controllers. It can see that $SO1$ gives the minimum energy consumption value among four and $SO2$ gives the maximum value. The difference value of energy consumption between $SO1$ and $SO4$ is small. Nevertheless $SO1$ gives the lower value of energy consumption than $SO4$, the settling time to desired temperature level and the demand PPD band is longer than $SO4$. From these results, it can conclude that user can choose their preference controller according to their requirement, i.e., if users want to achieve the desired temperature/thermal comfort level rapidly regardless of energy consumption, user may choose supervisory $SO4$. Otherwise they may choose $SO1$ or $SO2$ or $SO3$.

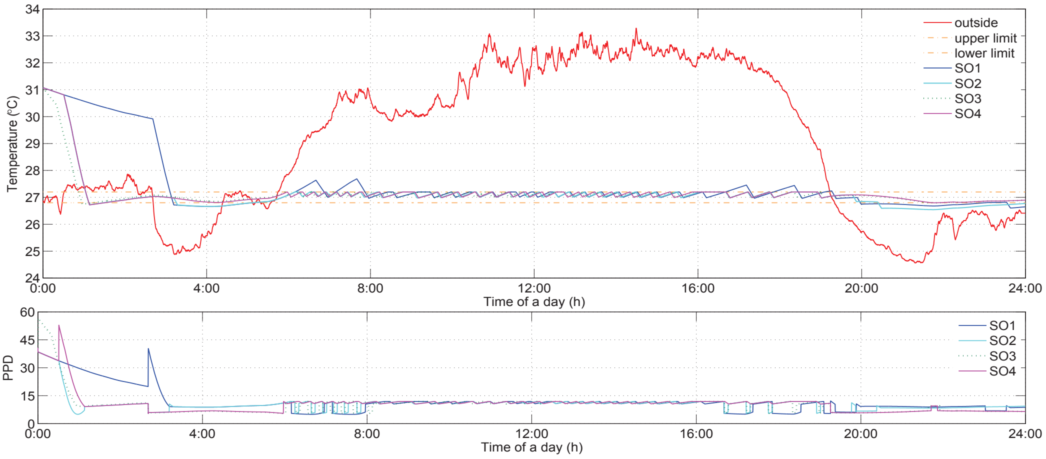


Figure 3.12: Room temperature variation and PPD under the different types of supervisory controllers.

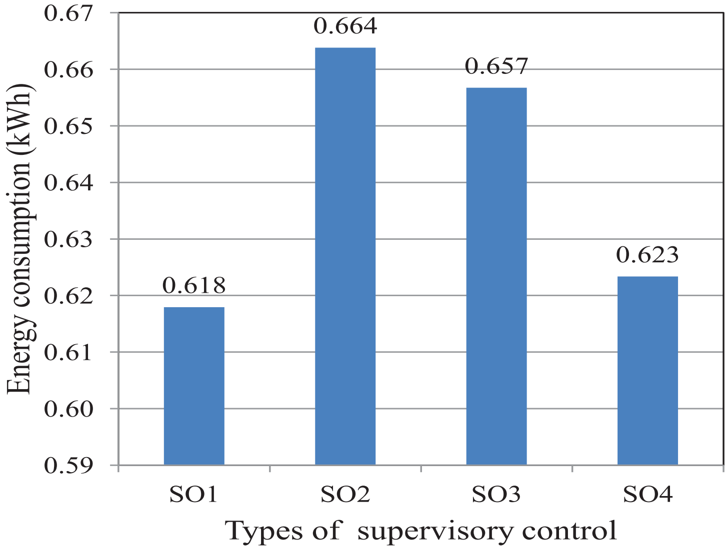


Figure 3.13: Energy consumption comparison with different types of supervisory controllers.

3.6.11 Setting Temperature and Energy Consumption

In this section, we make a short discussion on the relationship between setting temperature, PPD and energy consumption. Figure 3.14 shows that the simulation results of different setting (desired) temperature and their corresponding thermal discomfort values. Assume the demand PPD band is below 15%, it observe that the PPD values with the setting temperature of $27°C$ do not give the demand PPD band in the morning and

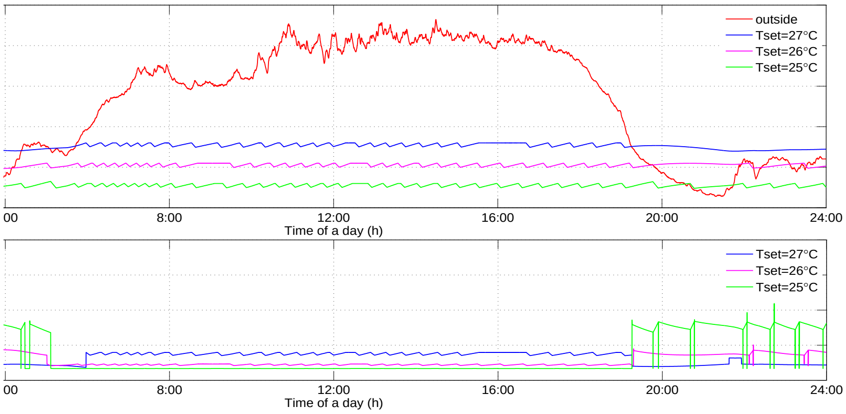


Figure 3.14: Setting temperature and corresponding PPD values.

night time although it gives the lowest PPD band at day time, at those time the outside temperature is low and the room temperature is controlled by none of the actuators. The PPD band of the other two setting temperature give within the demand band. It can see that PPD value with the setting temperature $26°C$ is lower than $27°C$ at day time (air-conditioning operation duration). However Figure3.15 shows that the energy consumption with the setting temperature $26°C$ is larger than with setting temperature $27°C$. Therefore, it is more preferable to choose the setting temperature as $27°C$ from the viewpoint of minimizing energy consumption without violating thermal discomfort. And hence, the setting temperature of HTC system in this paper is set as $27°C$.

3.7 Summary

In this chapter, design and implementation of CPS-based hybrid temperature control (HTC) system with multiple actuators is presented. HTC system is designed with supervisory control and PI controller. Investigation of the performance of the system on the regulation of room temperature with multiple actuators is conducted in terms of thermal discomfort, energy consumption and number of transitions. In this study, HTC system is upgraded by adding one by one actuator.

This study shows that the supervisory control could help to reduce the energy consumption of air-conditioner. It also observes that natural ventilation could not help to reduce the internal heat gain in day time during the summer season. However the power

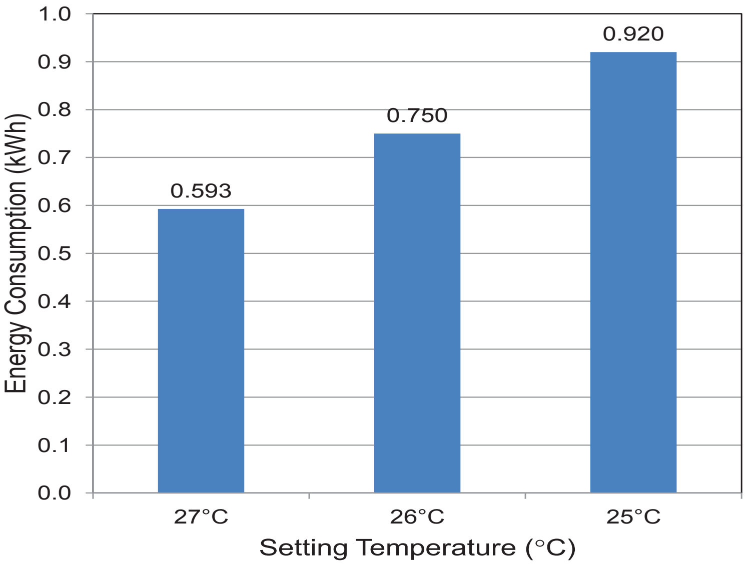


Figure 3.15: Comparison of energy consumption.

consumption of air-conditioner is reduced because of natural ventilation (opening window) at night time. Therefore, CPS-HTC system could help to reduce the power consumption of energy-consumed heating/cooling devices by allowing the actuators to cooperate to achieve the desired temperature without violating the occupant's thermal comfort. Moreover, the influence of curtain in room temperature control is studied and it shows that curtain could help to reduce the cooling/heating load. In addition, this chapter shows that energy consumption of air-conditioning system can reduce by increasing the setting temperature of air-conditioner in keeping the PPD value within demand band. To the best of my knowledge, the proposed CPS-based HTC shows that the energy consumption of heating/cooling devices can be reduced by allowing the interoperability among the actuators without affecting the occupant's thermal comfort.

Table 3.9: Symbol and definition of the modes and the differential equations govern the changes of room temperature in the refinement of each state.

Mode	Description	Rate of change of temperature
$m_0 = S_{aoff,foff,wcl,ccl}$	Room temperature is controlled by any actuator	$\dot{T}_r(t) = \frac{1}{C_i}(Q_{wal} + Q_{inf} + Q_{dth} + Q_{ss} + Q_{ocp})$
$m_1 = S_{aoff,foff,wcl,cop}$	Room temperature is controlled by only curtain	$\dot{T}_r(t) = \frac{1}{C_i}(Q_{wal} + Q_{inf} + Q_{dth} + Q_{ss} + Q_{ocp})$
$m_2 = S_{aoff,foff,wop,cop}$	Room temperature is controlled by window and curtain	$\dot{T}_r(t) = \frac{1}{C_i}(Q_{wal} + Q_{inf} + Q_{dth} + Q_{ss} + Q_{ocp} + Q_{wd})$
$m_3 = S_{aoff,fon,wcl,ccl}$	Room temperature is controlled by only fan	$\dot{T}_r(t) = \frac{1}{C_i}(Q_{wal} + Q_{inf} + Q_{dth} + Q_{ss} + Q_{ocp} + Q_{fa})$
$m_4 = S_{aoff,fon,wcl,cop}$	Room temperature is controlled by fan and curtain	$\dot{T}_r(t) = \frac{1}{C_i}(Q_{wal} + Q_{inf} + Q_{dth} + Q_{ss} + Q_{ocp} + Q_{fa})$
$m_5 = S_{aoff,fon,wop,cop}$	Room temperature is controlled by fan, window and curtain	$\dot{T}_r(t) = \frac{1}{C_i}(Q_{wal} + Q_{inf} + Q_{dth} + Q_{ss} + Q_{ocp} + Q_{fa} + Q_{wd})$
$m_6 = S_{aon,foff,wcl,ccl}$	Room temperature is controlled by only air-conditioner	$\dot{T}_r(t) = \frac{1}{C_i}(Q_{wal} + Q_{inf} + Q_{dth} + Q_{ss} + Q_{ocp} + Q_{ac})$
$m_7 = S_{aon,foff,wcl,cop}$	Room temperature is controlled by air-conditioner and curtain	$\dot{T}_r(t) = \frac{1}{C_i}(Q_{wal} + Q_{inf} + Q_{dth} + Q_{ss} + Q_{ocp} + Q_{ac})$
$m_8 = S_{aon,fon,wcl,ccl}$	Room temperature is controlled by air-conditioner and fan	$\dot{T}_r(t) = \frac{1}{C_i}(Q_{wal} + Q_{inf} + Q_{dth} + Q_{ss} + Q_{ocp} + Q_{ac} + Q_{fa})$
$m_9 = S_{aon,fon,wcl,cop}$	Room temperature is controlled by air-conditioner, fan and curtain	$\dot{T}_r(t) = \frac{1}{C_i}(Q_{wal} + Q_{inf} + Q_{dth} + Q_{ss} + Q_{ocp} + Q_{ac} + Q_{fa})$

Table 3.10: Transitions and their associated guards (Supervisory Controller Type 1: SO1).

Transition	Transition condition
δ_{01}: mode $m0$ to mode $m1$	$c1 \,\&\,\& \,not(c4)$
δ_{03}: mode $m0$ to mode $m3$	$not(c1) \,\&\,\& \,not(c4) \,\&\,\& \,c6 \,\&\,\& \,c3$
δ_{06}: mode $m0$ to mode $m6$	$not(c1) \,\&\,\& \,(not(c2) \Vert c2) \,\&\,\& \,not(c4) \,\&\,\& \,not(c6) \,\&\,\& \,c3$
δ_{10}: mode $m1$ to mode $m0$	$c4$
δ_{12}: mode $m1$ to mode $m2$	$c1 \,\&\,\& \,c2 \,\&\,\& \,not(c4) \,\&\,\& \,(c6 \Vert not(c6))$
δ_{14}: mode $m1$ to mode $m4$	$not(c1) \,\&\,\& \,not(c2) \,\&\,\& \,c6 \,\&\,\& \,c3$
δ_{16}: mode $m1$ to mode $m6$	$not(c1) \,\&\,\& \,(not(c2) \Vert c2) \,\&\,\& \,not(c4) \,\&\,\& \,not(c6) \,\&\,\& \,c3$
δ_{17}: mode $m1$ to mode $m7$	$c1 \,\&\,\& \,(not(c2) \Vert c2) \,\&\,\& \,not(c4) \,\&\,\& \,not(c6) \,\&\,\& \,c3$
δ_{18}: mode $m1$ to mode $m8$	$not(c1) \,\&\,\& \,(not(c2) \Vert c2) \,\&\,\& \,not(c4) \,\&\,\& \,c6 \,\&\,\& \,c3$
δ_{19}: mode $m1$ to mode $m9$	$c1 \,\&\,\& \,(not(c2) \Vert c2) \,\&\,\& \,not(c4) \,\&\,\& \,c6 \,\&\,\& \,c3$
δ_{20}: mode $m2$ to mode $m0$	$c4$
δ_{23}: mode $m2$ to mode $m3$	$(timer > Time_{wd}) \,\&\,\& \,not(c1) \,\&\,\& \,not(c2) \,\&\,\& \,not(c4) \,\&\,\& \,c6 \,\&\,\& \,c3$
δ_{24}: mode $m2$ to mode $m4$	$(timer > Time_{wd}) \,\&\,\& \,c1 \,\&\,\& \,not(c2) \,\&\,\& \,not(c4) \,\&\,\& \,c6 \,\&\,\& \,c3$
δ_{25}: mode $m2$ to mode $m5$	$(timer > Time_{wd}) \,\&\,\& \,c1 \,\&\,\& \,c2 \,\&\,\& \,not(c4) \,\&\,\& \,(c6 \Vert not(c6))$
δ_{26}: mode $m2$ to mode $m6$	$(timer > Time_{wd}) \,\&\,\& \,not(c1) \,\&\,\& \,(not(c2) \Vert c2) \,\&\,\& \,not(c4) \,\&\,\& \,not(c6) \,\&\,\& \,c3$
δ_{27}: mode $m2$ to mode $m7$	$(timer > Time_{wd}) \,\&\,\& \,c1 \,\&\,\& \,(not(c2) \Vert c2) \,\&\,\& \,not(c4) \,\&\,\& \,not(c6) \,\&\,\& \,c3$
δ_{30}: mode $m3$ to mode $m0$	$c4$

Transition	Transition condition
δ_{35}: mode $m3$ to mode $m5$	$c1 \,\&\&\, c2 \,\&\&\, not(c4) \,\&\&\, (c6 \parallel not(c6))$
δ_{36}: mode $m3$ to mode $m6$	$(timer > Time_{fan}) \,\&\&\, not(c1) \,\&\&\, (not(c2) \parallel c2) \,\&\&\, not(c4) \,\&\&\, not(c6) \,\&\&\, c3$
δ_{37}: mode $m3$ to mode $m7$	$(timer > Time_{fan}) \,\&\&\, c1 \,\&\&\, (not(c2) \parallel c2) \,\&\&\, not(c4) \,\&\&\, not(c6) \,\&\&\, c3$
δ_{38}: mode $m3$ to mode $m8$	$(timer > Time_{fan}) \,\&\&\, not(c1) \,\&\&\, (not(c2) \parallel c2) \,\&\&\, not(c4) \,\&\&\, c6 \,\&\&\, c3$
δ_{39}: mode $m3$ to mode $m9$	$(timer > Time_{fan}) \,\&\&\, c1 \,\&\&\, (not(c2) \parallel c2) \,\&\&\, not(c4) \,\&\&\, c6 \,\&\&\, c3$
δ_{40}: mode $m4$ to mode $m0$	$c4$
δ_{45}: mode $m4$ to mode $m5$	$c1 \,\&\&\, c2 \,\&\&\, not(c4) \,\&\&\, (c6 \parallel not(c6))$
δ_{46}: mode $m4$ to mode $m6$	$(timer > Time_{fan}) \,\&\&\, not(c1) \,\&\&\, (not(c2) \parallel c2) \,\&\&\, not(c4) \,\&\&\, not(c6)$
δ_{47}: mode $m4$ to mode $m7$	$(timer > Time_{fan}) \,\&\&\, c1 \,\&\&\, (not(c2) \parallel c2) \,\&\&\, not(c4) \,\&\&\, not(c6)$
δ_{48}: mode $m4$ to mode $m8$	$(timer > Time_{fan}) \,\&\&\, not(c1) \,\&\&\, (not(c2) \parallel c2) \,\&\&\, not(c4) \,\&\&\, c6$
δ_{49}: mode $m4$ to mode $m9$	$(timer > Time_{fan}) \,\&\&\, c1 \,\&\&\, (not(c2) \parallel c2) \,\&\&\, not(c4) \,\&\&\, c6$
δ_{50}: mode $m5$ to mode $m0$	$c4$
δ_{56}: mode $m5$ to mode $m6$	$not(c1) \,\&\&\, (not(c2) \parallel c2) \,\&\&\, not(c4) \,\&\&\, not(c6)$
δ_{57}: mode $m5$ to mode $m7$	$c1 \,\&\&\, (not(c2) \parallel c2) \,\&\&\, not(c4) \,\&\&\, not(c6)$
δ_{58}: mode $m5$ to mode $m8$	$not(c1) \,\&\&\, (not(c2) \parallel c2) \,\&\&\, not(c4) \,\&\&\, c6 \,\&\&\, c3$
δ_{59}: mode $m5$ to mode $m9$	$c1 \,\&\&\, (not(c2) \parallel c2) \,\&\&\, not(c4) \,\&\&\, c6 \,\&\&\, c3$
δ_{60}: mode $m6$ to mode $m0$	$c4$

Transition	Transition condition
δ_{62}: mode $m6$ to mode $m2$	$c1$ & & $c2$ & & $not(c4)$ & & $(c6 \parallel not(c6))$
δ_{68}: mode $m6$ to mode $m8$	$not(c1)$ & & $(not(c2) \parallel c2)$ & & $not(c4)$ & & $c6$
δ_{69}: mode $m6$ to mode $m9$	$c1$ & & $(not(c2) \parallel c2)$ & & $not(c4)$ & & $c6$
δ_{70}: mode $m7$ to mode $m0$	$c4$
δ_{72}: mode $m7$ to mode $m2$	$c1$ & & $c2$ & & $not(c4)$ & & $(c6 \parallel not(c6))$
δ_{76}: mode $m7$ to mode $m6$	$not(c1)$ & & $(not(c2) \parallel c2)$ & & $not(c4)$ & & $not(c6)$
δ_{78}: mode $m7$ to mode $m8$	$not(c1)$ & & $(not(c2) \parallel c2)$ & & $not(c4)$ & & $c6$ & & $c3$
δ_{79}: mode $m7$ to mode $m9$	$c1$ & & $(not(c2) \parallel c2)$ & & $not(c4)$ & & $c6$ & & $c3$
δ_{80}: mode $m8$ to mode $m0$	$c4$
δ_{90}: mode $m9$ to mode $m0$	$c4$

Table 3.11: Transitions and their associated guards (Supervisory Controller Type 2: SO2).

Transition	Transition condition
δ_{01}: mode $m0$ to mode $m1$	$c1$ & & $not(c4)$
δ_{06}: mode $m0$ to mode $m6$	$not(c1)$ & & $(not(c2) \Vert c2)$ $not(c4)$ & & $not(c6)$ & & $c3$
δ_{08}: mode $m0$ to mode $m8$	$not(c1)$ & & $(not(c2) \Vert c2)$ $not(c4)$ & & $c6$ & & $c3$
δ_{09}: mode $m0$ to mode $m9$	$c1$ & & $(not(c2) \Vert c2)$ & & $not(c4)$ & & $c6$ & & $c3$
δ_{10}: mode $m1$ to mode $m0$	$c4$
δ_{12}: mode $m1$ to mode $m2$	$c1$ & & $c2$ & & $not(c4)$ & & $(c6 \Vert not(c6))$
δ_{16}: mode $m1$ to mode $m6$	$not(c1)$ & & $(not(c2) \Vert c2)$ $not(c4)$ & & $not(c6)$ & & $c3$
δ_{17}: mode $m1$ to mode $m7$	$c1$ & & $(not(c2) \Vert c2)$ & & $not(c4)$ & & $not(c6)$ & & $c3$
δ_{18}: mode $m1$ to mode $m8$	$not(c1)$ & & $(not(c2) \Vert c2)$ $not(c4)$ & & $c6$ & & $c3$
δ_{19}: mode $m1$ to mode $m9$	$c1$ & & $(not(c2) \Vert c2)$ & & $not(c4)$ & & $c6$ & & $c3$
δ_{20}: mode $m2$ to mode $m0$	$c4$
δ_{25}: mode $m2$ to mode $m5$	$(timer > Time_{wd})$ & & $c1$ & & $c2$ & & $not(c4)$ & & $(c6 \Vert not(c6))$ & & $c3$
δ_{26}: mode $m2$ to mode $m6$	$(timer > Time_{wd})$ & & $not(c1)$ & & $(not(c2) \Vert c2)$ $not(c4)$ & & $not(c6)$ & & $c3$
δ_{27}: mode $m2$ to mode $m7$	$(timer > Time_{wd})$ & & $c1$ & & $(not(c2) \Vert c2)$ & & $not(c4)$ & & $not(c6)$ & & $c3$
δ_{28}: mode $m2$ to mode $m8$	$(timer > Time_{wd})$ & & $not(c1)$ & & $(not(c2) \Vert c2)$ $not(c4)$ & & $c6$ & & $c3$
δ_{29}: mode $m2$ to mode $m9$	$(timer > Time_{wd})$ & & $c1$ & & $(not(c2) \Vert c2)$ & & $not(c4)$ & & $c6$ & & $c3$
δ_{50}: mode $m5$ to mode $m0$	$c4$ & & $(timer > 30)$

Transition	Transition condition
δ_{56}: mode $m5$ to mode $m6$	$not(c1)$ & & $(not(c2) \parallel c2)$ $not(c4)$ & & $not(c6)$
δ_{57}: mode $m5$ to mode $m7$	$c1$ & & $(not(c2) \parallel c2)$ & & $not(c4)$ & & $not(c6)$
δ_{58}: mode $m5$ to mode $m8$	$not(c1)$ & & $(not(c2) \parallel c2)$ $not(c4)$ & & $c6$
δ_{59}: mode $m5$ to mode $m9$	$c1$ & & $(not(c2) \parallel c2)$ & & $not(c4)$ & & $c6$
δ_{60}: mode $m6$ to mode $m0$	$c4$
δ_{62}: mode $m6$ to mode $m2$	$c1$ & & $c2$ & & $not(c4)$ & & $(c6 \parallel not(c6))$
δ_{68}: mode $m6$ to mode $m8$	$not(c1)$ & & $(not(c2) \parallel c2)$ $not(c4)$ & & $c6$
δ_{69}: mode $m6$ to mode $m9$	$c1$ & & $(not(c2) \parallel c2)$ & & $not(c4)$ & & $c6$
δ_{70}: mode $m7$ to mode $m0$	$c4$
δ_{72}: mode $m7$ to mode $m2$	$c1$ & & $c2$ & & $not(c4)$ & & $(c6 \parallel not(c6))$
δ_{76}: mode $m7$ to mode $m6$	$not(c1)$ & & $(not(c2) \parallel c2)$ $not(c4)$ & & $not(c6)$
δ_{78}: mode $m7$ to mode $m8$	$not(c1)$ & & $(not(c2) \parallel c2)$ $not(c4)$ & & $c6$
δ_{79}: mode $m7$ to mode $m9$	$c1$ & & $(not(c2) \parallel c2)$ $not(c4)$ & & $c6$
δ_{80}: mode $m8$ to mode $m0$	$c4$
δ_{90}: mode $m9$ to mode $m0$	$c4$

Table 3.12: Transitions and their associated guards (Supervisory Controller Type 3: SO3).

Transition	Transition condition
δ_{01}: mode $m0$ to mode $m1$	$c1\ \&\ \&\ not(c4)$
δ_{06}: mode $m0$ to mode $m6$	$not(c1)\ \&\ \&\ (not(c2) \parallel c2)\ not(c4)\ \&\ \&\ not(c6)\ \&\ \&\ c3$
δ_{08}: mode $m0$ to mode $m8$	$not(c1)\ \&\ \&\ (not(c2) \parallel c2)\ not(c4)\ \&\ \&\ c6\ \&\ \&\ c3$
δ_{09}: mode $m0$ to mode $m9$	$c1\ \&\ \&\ (not(c2) \parallel c2)\ \&\ \&\ not(c4)\ \&\ \&\ c6\ \&\ \&\ c3$
δ_{10}: mode $m1$ to mode $m0$	$c4$
δ_{12}: mode $m1$ to mode $m2$	$c1\ \&\ \&\ c2\ \&\ \&\ not(c4)\ \&\ \&\ (c6 \parallel not(c6))$
δ_{16}: mode $m1$ to mode $m6$	$not(c1)\ \&\ \&\ (not(c2) \parallel c2)\ not(c4)\ \&\ \&\ not(c6)\ \&\ \&\ c3$
δ_{17}: mode $m1$ to mode $m7$	$c1\ \&\ \&\ (not(c2) \parallel c2)\ \&\ \&\ not(c4)\ \&\ \&\ not(c6)\ \&\ \&\ c3$
δ_{18}: mode $m1$ to mode $m8$	$not(c1)\ \&\ \&\ (not(c2) \parallel c2)\ not(c4)\ \&\ \&\ c6\ \&\ \&\ c3$
δ_{19}: mode $m1$ to mode $m9$	$c1\ \&\ \&\ (not(c2) \parallel c2)\ \&\ \&\ not(c4)\ \&\ \&\ c6\ \&\ \&\ c3$
δ_{20}: mode $m2$ to mode $m0$	$c4$
δ_{26}: mode $m2$ to mode $m6$	$not(c1)\ \&\ \&\ (not(c2) \parallel c2)\ \&\ \&\ not(c4)\ \&\ \&\ not(c6)\ \&\ \&\ c3$
δ_{27}: mode $m2$ to mode $m7$	$c1\ \&\ \&\ (not(c2) \parallel c2)\ \&\ \&\ not(c4)\ \&\ \&\ not(c6)\ \&\ \&\ c3$
δ_{28}: mode $m2$ to mode $m8$	$not(c1)\ \&\ \&\ (not(c2) \parallel c2)\ \&\ \&\ not(c4)\ \&\ \&\ c6\ \&\ \&\ c3$
δ_{29}: mode $m2$ to mode $m9$	$c1\ \&\ \&\ (not(c2) \parallel c2)\ \&\ \&\ not(c4)\ \&\ \&\ c6\ \&\ \&\ c3$
δ_{60}: mode $m6$ to mode $m0$	$c4$
δ_{62}: mode $m6$ to mode $m2$	$c1\ \&\ \&\ c2\ \&\ \&\ not(c4)\ \&\ \&\ (c6 \parallel not(c6))$
δ_{68}: mode $m6$ to mode $m8$	$not(c1)\ \&\ \&\ (not(c2) \parallel c2)\ not(c4)\ \&\ \&\ c6$
δ_{69}: mode $m6$ to mode $m9$	$c1\ \&\ \&\ (not(c2) \parallel c2)\ \&\ \&\ not(c4)\ \&\ \&\ c6$
δ_{70}: mode $m7$ to mode $m0$	$c4$

Transition	Transition condition
δ_{72}: mode $m7$ to mode $m2$	$c1$ & & $c2$ & & $not(c4)$ & & $(c6 \parallel not(c6))$
δ_{76}: mode $m7$ to mode $m6$	$not(c1)$ & & $(not(c2) \parallel c2)$ $not(c4)$ & & $not(c6)$
δ_{78}: mode $m7$ to mode $m8$	$not(c1)$ & & $(not(c2) \parallel c2)$ $not(c4)$ & & $c6$
δ_{79}: mode $m7$ to mode $m9$	$c1$ & & $(not(c2) \parallel c2)$ $not(c4)$ & & $c6$
δ_{80}: mode $m8$ to mode $m0$	$c4$
δ_{90}: mode $m9$ to mode $m0$	$c4$

Table 3.13: Transitions and their associated guards (Supervisory Controller Type 3: SO4).

Transition	Transition condition
δ_{01}: mode $m0$ to mode $m1$	$c1$ & & $not(c4)$
δ_{06}: mode $m0$ to mode $m6$	$not(c1)$ & & $(not(c2) \parallel c2)$ $not(c4)$ & & $not(c6)$ & & $c3$
δ_{10}: mode $m1$ to mode $m0$	$c4$
δ_{12}: mode $m1$ to mode $m2$	$c1$ & & $c2$ & & $not(c4)$ & & $(c6 \parallel not(c6))$
δ_{16}: mode $m1$ to mode $m6$	$not(c1)$ & & $(not(c2) \parallel c2)$ $not(c4)$ & & $not(c6)$ & & $c3$
δ_{17}: mode $m1$ to mode $m7$	$c1$ & & $(not(c2) \parallel c2)$ & & $not(c4)$ & & $not(c6)$ & & $c3$
δ_{20}: mode $m2$ to mode $m0$	$c4$ & & $(timer > 30)$
δ_{26}: mode $m2$ to mode $m6$	$(timer > Time_{wd})$ & & $not(c1)$ & & $(not(c2) \parallel c2)$ & & $not(c4)$ & & $(c6 \parallel not(c6))$
δ_{27}: mode $m2$ to mode $m7$	$(timer > Time_{wd})$ & & $c1$ & & $(not(c2) \parallel c2)$ & & $not(c4)$ & & $(c6 \parallel not(c6))$ & & $c3$
δ_{60}: mode $m6$ to mode $m0$	$c4$
δ_{62}: mode $m6$ to mode $m2$	$c1$ & & $c2$ & & $not(c4)$ & & $(c6 \parallel not(c6))$
δ_{70}: mode $m7$ to mode $m0$	$c4$
δ_{72}: mode $m7$ to mode $m2$	$c1$ & & $c2$ & & $not(c4)$ & & $(c6 \parallel not(c6))$
δ_{76}: mode $m7$ to mode $m6$	$not(c1)$ & & $(not(c2) \parallel c2)$ $not(c4)$ & & $(c6 \parallel not(c6))$

Chapter 4

Evaluation of the CPS-based Hybrid Temperature Control System

4.1 Introduction

Nowadays, the advanced technology allows us to live in a more comfortable and smart environment. At the same time, the demand such as: comfort and control aspects, equipment loads and minimum energy efficiency increase speedily. Recently, the advanced technology called Cyber-physical Systems (CPS) brings to achieve these high demands in home network.

CPS is a tight integration of computation, communication, and control for active interaction between physical and cyber (computational) elements. In [1], CPS tend to feature a tight coupling between physical and software components and may be required to operate for long periods without human intervention. As CPS continuously interacts with the physical world, the behaviour of a CPS must change in order to maintain conditions and operational contexts.

Since the need for comfort control at home is widely recognized today, control of thermal environment is needed form the viewpoint of comfort, health reasons and satisfaction. In Chapter 3, design and implementation of CPS-based temperature control system with multiple actuators is presented. Following these, the performance of the system in room temperature control is studied by conducting the simulation in Matlab/Simulink software. In this chapter, the focus of the study is the evaluation of the system proposed in

Chapter 3 by conducting the experiments in real experiment house. Then, the evaluation of the system is done by analysing the operation modes of the system and the variation of the temperature with supervisory control. Then simulation results are compared with experiment results to show the validation.

The objectives of this Chapter are

1. To show the validation of the model with the simulation and experiment results.
2. To analyze the operation modes this will help in designing the control algorithm for the supervisory controller.
3. To show how CPS integrate the physical and cyber world by implementing the system in real smart house environment, iHouse.

The remainder of this Chapter is organized as follows. Section 4.2 presents the preliminary works related to this research. In Section 4.3, validation of the operation modes composed with four actuators is carried out. Section 4.4 shows the evaluation of the system with supervisory control and summarizes the Chapter in Section 4.5.

4.2 Preliminaries

In this section, the requirements for simulation and experiment environments are presented. The architectures of the simulation and experiment environments, thermal simulator and experiment house, iHouse are described.

4.2.1 Simulation Environment

Architecture

The design and architecture of CPS-based temperature control system presented in Section 3.3, Chapter 3 are considered. The system is based on the concept of feedback control over wireless sensor and actuator network (WSAN). In this temperature control system, the instantaneous room temperature is always sense by the sensors and these sensed data is averaged and compared with the desired temperature. Following these, the supervisory controller computes the predefined algorithm with the feedback data and then decides the control commands to make the desired changes to the physical environment. Since

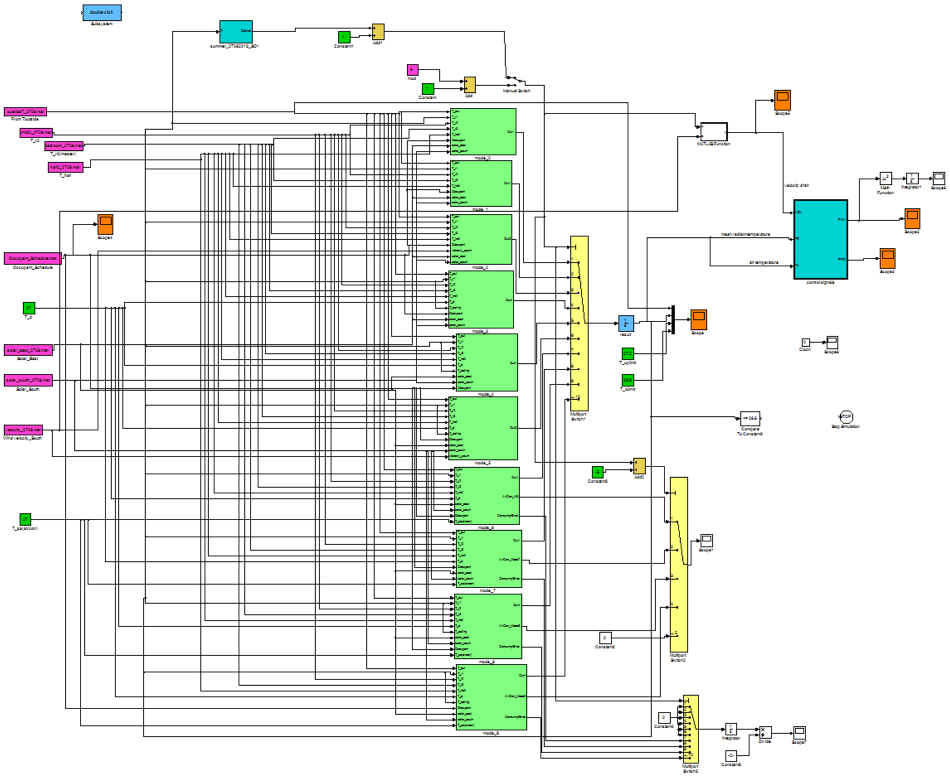


Figure 4.1: Room model in simulink.

the air-conditioner considered in this thesis is designed with PI controller, PI controller adjusts the amount of heat load produced by air-conditioner according to the error temperature every time the air-conditioner is triggered by the supervisory controller.

Thermal Simulator Thermal simulator is a simulator which can simulate thermal environment of house. In this research, thermal simulator that is created based on the parameters of real house is employed and the evolution of thermal load is close to experience in real house. In the simulation, the raw data from the experiments such as outside temperature, solar radiation, wind velocity and raining status are used as the input data file to the simulator. The simulator is implemented with MATLAB Simulink tools and the thermal model explained in Section 3.4, Chapter 3 is applied. Figure 4.1 depicts the simulation environment in Simulink. Figure 4.2 shows the implementation of air-conditioner which is designed with PI controller and regulated the heating/cooling load of air-conditioner. It can say that the air-conditioner is inverter type and PI ensure the heat distribution from the air-conditioner.

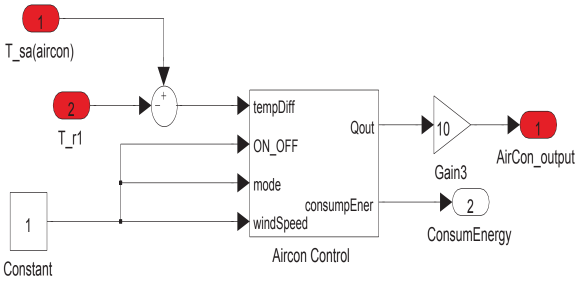


Figure 4.2: Overview of air-conditioner in simulink.

4.2.2 Experiment Environment

Architecture

Figure 4.3 shows the basic architecture of CPS-based hybrid temperature control system implemented in real experiment house, iHouse. In iHouse, a variety of sensors, such as power consumption sensors, water-flow sensors, temperature sensor and the brightness sensors are built into. Consider for the temperature control system developed in this thesis, sensors designed with ECHONET protocol are embedded on each temperature control devices, air-condition, window, curtain and fan. Normally total number of 8 sensors is set on each corner of ceiling and floor of the room. Home appliance network employed in iHouse not only control the home appliance usage, but also environment information for example, the outside temperature, solar radiation, rain level, etc.

In this research, to transfer the data in home appliance sensor network, sensors send their sending data to the sensor controlling ECHONET device via the wired network. ECHONET is an international home network protocol standards used to control, monitor, and gather information from equipment and sensors that are usually found in the home. Through the ECHONET (Bluetooth) and ECHONET Gateway, the data sensed by the sensors are send to the TemperatureDB (Temperature Database). Then, TemperatureDB transfer the data through the Internal House LAN network to the Controller to process the computation. The Controller also received the outside environment data by using the Data Logger and the information of the ECHONET devices (actuators) through the ECHONET Lite protocol (Ethernet); the updated version of ECHONET. The Controller send back the control signals to the actuators through the ECHONET Lite protocol.
House, iHouse To evaluate the proposed CPS-based temperature control system with multiple actuators and to verify how CPS integrates the cyber and physical world, the

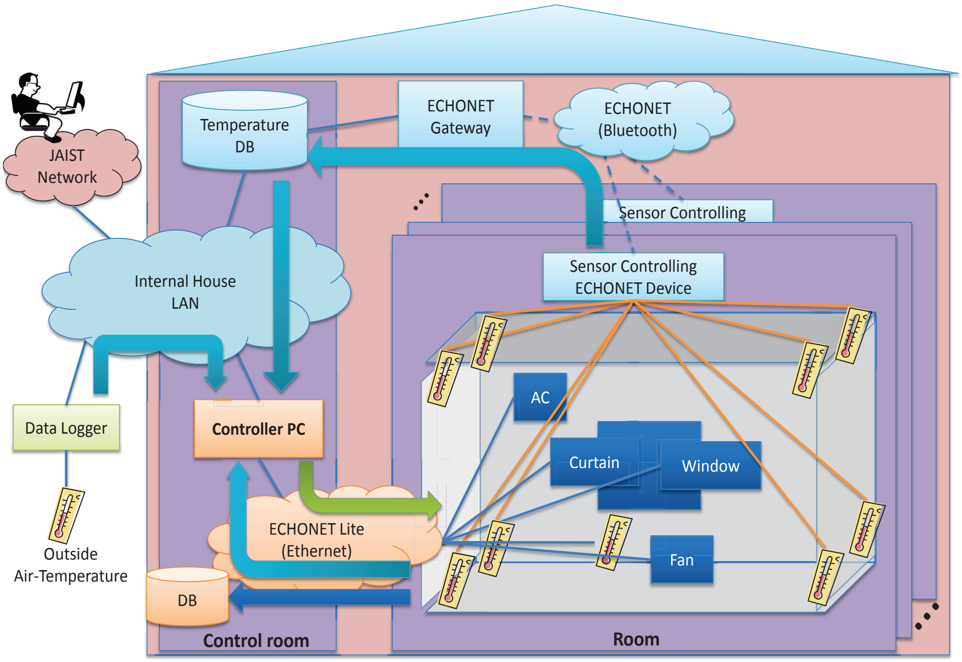


Figure 4.3: System architecture in experiment environment.

Figure 4.4: The smart house, iHouse,used for experiment.

implementation and experimentation are conducted in real smart house, iHouse. The iHouse is designed for the development of the next-generation home network system. iHouse is located at Nomi city, Ishikawa prefecture, Japan. It has two floors measuring 107.76 m2, more than 250 sensors and home appliances are connected through Energy Conservation and the Home care Network (ECHONET), Universal Plug and Play (UPnP), and Zigbee. A photograph of iHouse is presented in Figure 4.4. A sketch of experiment and simulation room is same as presented in Chapter 3.

Table 4.1: Status of modes (0 means off/close, 1 means on/open.)

Modes	Air-conditioner	fan	Window	Curtain
mode 0	0	0	0	0
mode 1	0	0	0	1
mode 2	0	0	1	1
mode 3	0	1	0	0
mode 4	0	1	0	1
mode 5	0	1	1	1
mode 6	1	0	0	0
mode 7	1	0	0	1
mode 8	1	1	0	0
mode 9	1	1	0	1

4.3 Evaluation the Operation Modes

This section shows the validation of the model by analyzing the operation modes. The organization of modes for HTC system with four actuators is first explained. Following this, model validation is show by conducting the simulation and experiment for 5 operation modes: mode 0, mode 1, mode 2, mode 3 and mode 6.

4.3.1 Defining the Operation Modes

In this study, the temperature control system with four actuators, air-conditioner, window, fan without supervisory is employed. As explained in Chapter 3, Section 3.6.4, the hybrid automaton for such kind of temperature controls system is composed with 16 operation modes. However, in this section, the operations of only 5 modes are studies. The formulation of combination of operation mode with 4 actuators and its definition is explained in Table 4.1.

4.3.2 Model Validation

The validation of the model by conducting the simulation and experiment for 5 modes: mode 0, mode 1, mode 2, mode 3 and mode 6. The experiments were done at the smart house experiment house, iHouse. In this study, MATLAB/Simulink tools is used for simulation. The experiments were done in different days for different modes either on/off or open/close the actuators. The simulation and experiment times are from 0:00 to 24:00 hours (one day duration). Form the experiment results, the parameters for simulation are correlated. The error value could reduce between the simulation and experiment results within -1 and +1 limits.

Since the experiments were done on the days of summer, except the some rainy days, the outside temperature and solar heat gain in the room are high in day time mostly. Therefore, the room at day time for mode 0, mode 1, mode 2 and mode 3 are very high. In mode 3, the changes of room temperature is small because of the usage of fan even the outside temperature have many variation. The temperature is kept at some point and could not reduced the temperature by using the fan. Only mode 6 can reduce the room temperature to the desired point. On that day, the operation was done from 9:00 to 24:00 hour. In simulation, the cooling load is getting small with the small value of error temperature, and the room temperature is settle at desired point. However, in experiment, the room temperature have some variation and getting low continuously. Figure 4.5 to 4.9 show the comparison between the simulation and experiment results and the error temperature between the two results.

4.3.3 Mode Analysing

In this section, the changes of room temperature for different modes are studied. The simulation is study is done for one day. From this study, the modes that are not much effect the room temperature are eliminated and it can observe the best conditions for defining the policies in supervisory controller. From the simulation results, it can see that mode 0 to mode 5 can be used in the morning time and night time. Among them, mode 2 and mode 5 help to reduce the room temperature under the condition of the outside temperature is lower than $26°C$ and the solar radiation value is zero. However, they could not help to reduce the temperature until to reach the desired point. Another reason is

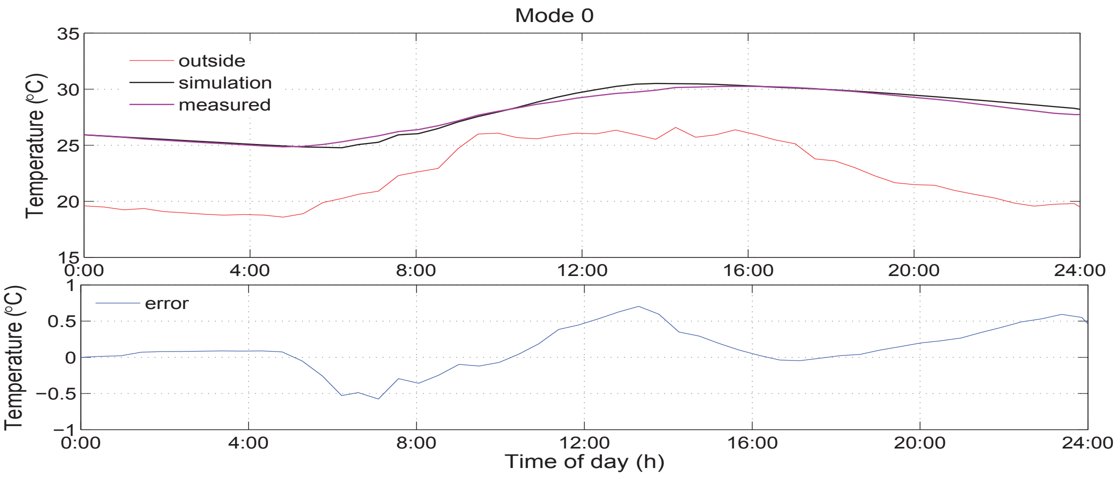


Figure 4.5: Simulated and measured temperature of mode 0. (June 24, 2013).

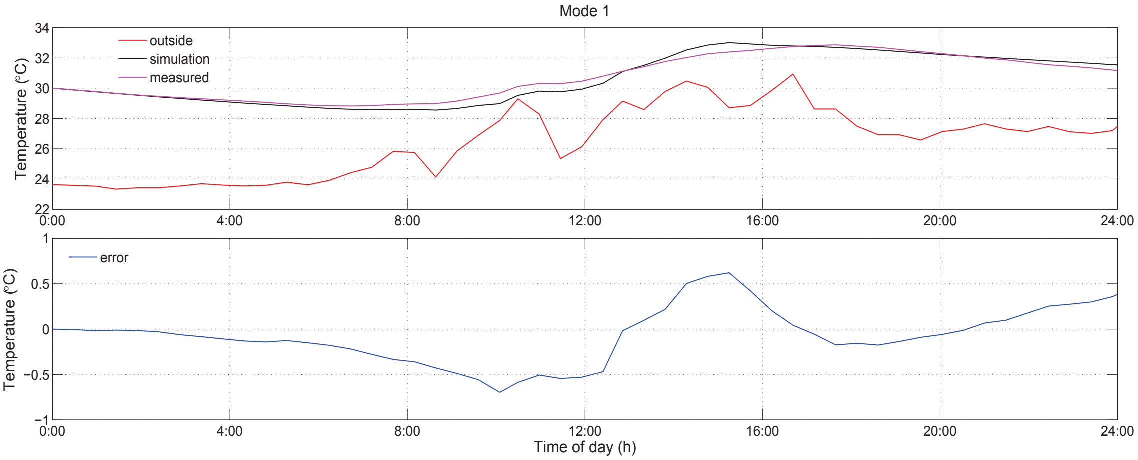


Figure 4.6: Simulated and measured temperature of mode 1. (July 07, 2013).

that the initial room temperature at the simulation starting time is very large and the outside temperature was also rather high.

Figure 4.10 and Figure 4.11show the analysing of 10 operation modes. It is observe that only the modes who include the air-conditioning operation (mode 6, 7, 8, 9) can help to reduce the room temperature.

4.4 System Evaluation with Supervisory Control

In this section, the simulation and experiment results of room temperature control with supervisory controller designed with three actuators; air-conditioner, window and curtain;

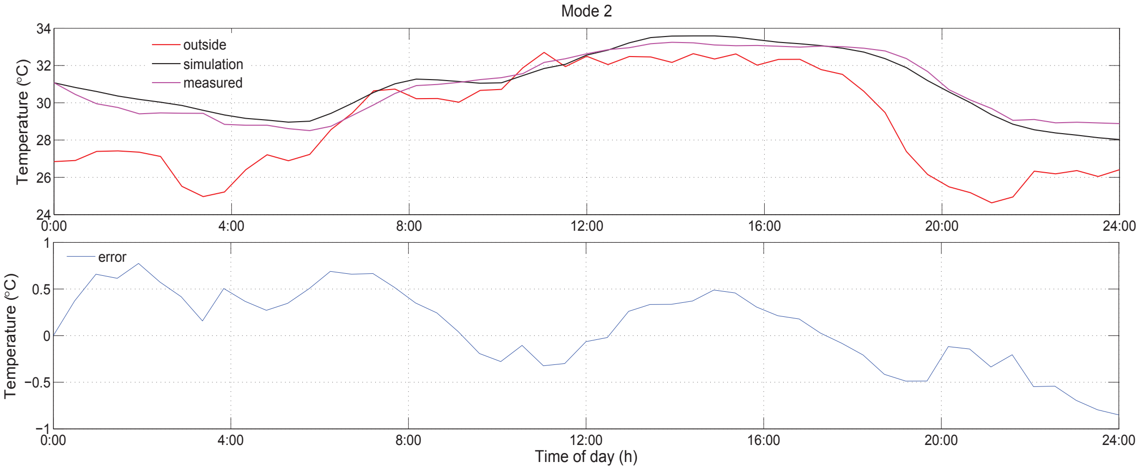


Figure 4.7: Simulated and measured temperature of mode 2. (July 08, 2013).

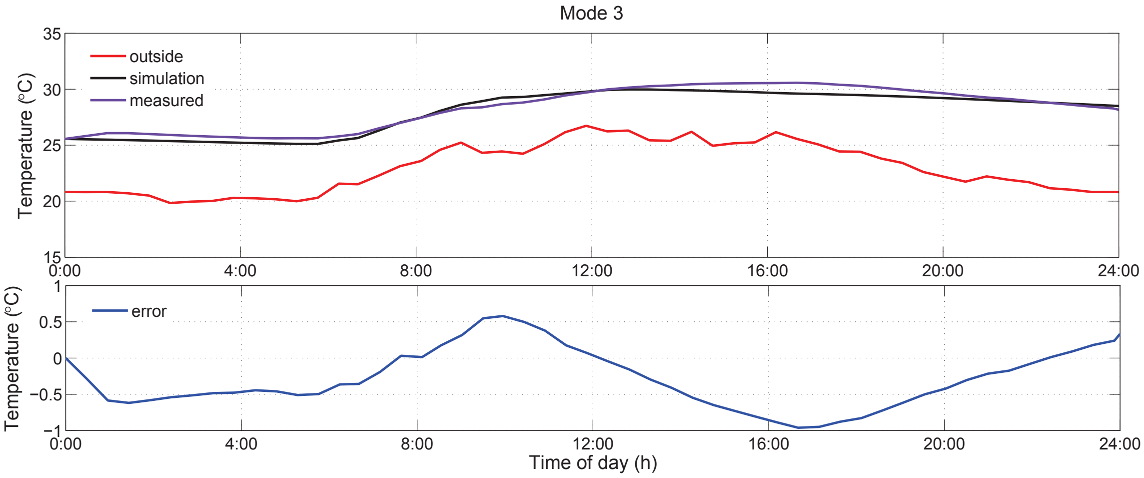


Figure 4.8: Simulated and measured temperature of mode 3. (June 28, 2013).

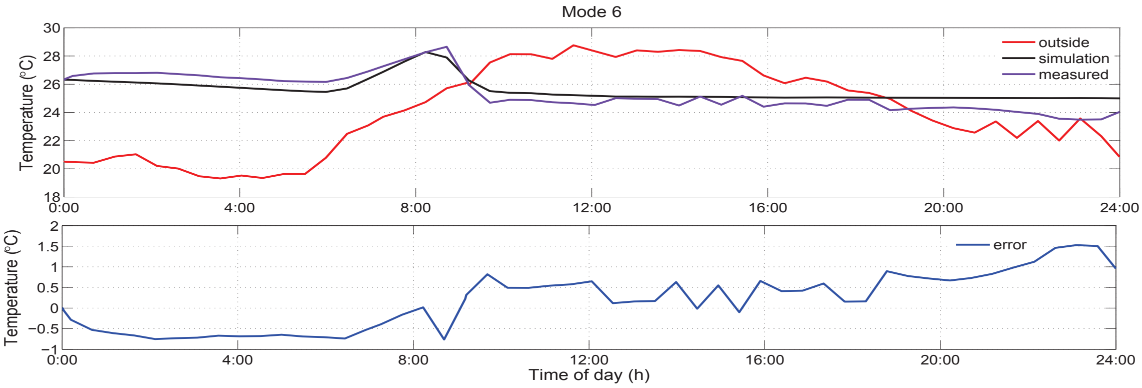


Figure 4.9: Simulated and measured temperature of mode 6. (June 30, 2013).

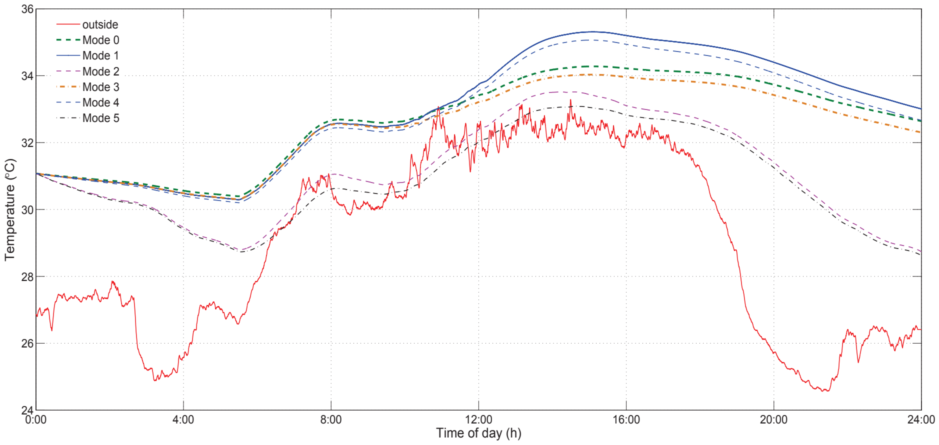


Figure 4.10: Analysis from mode 0 to mode 5.(July 08, 2013).

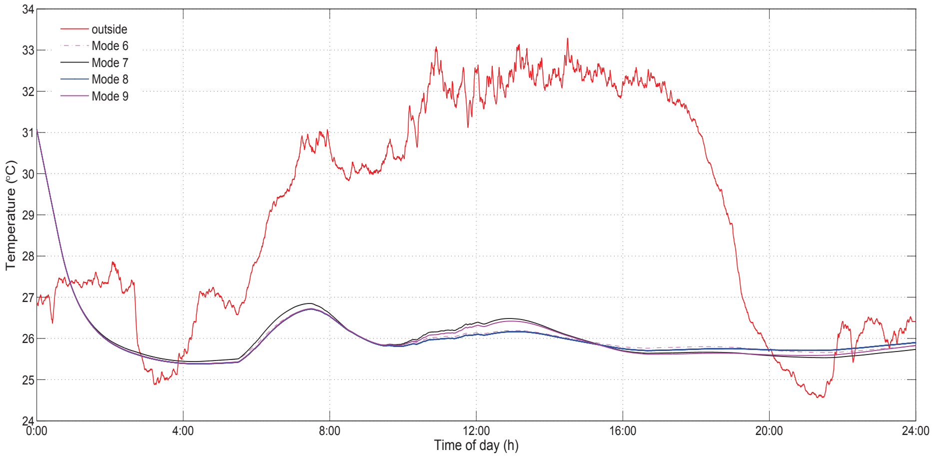


Figure 4.11: Analysis from mode 6 to mode 9. (July 08, 2013).

is presented.

4.4.1 Supervisory Control

A supervisory control is a class of hybrid systems. A supervisory control decides which actuator should be active at each time instant based on the calculation of the predefined algorithm and feedback parameters. In this Chapter, the supervisory control designed with three actuator; air-conditioner, window and curtain; for winter season is used. The symbol and definition of the modes and the differential equations govern the changes of the room temperature in the refinement of each state is applied as explained Table in Chapter 3, Section 3.6.3. Defined conditions for mode transition in Table 4.2 is explained.

Figure 4.12: Air-conditioner mounted with sensor.

The transition and their associated guards are expressed in Table 4.3.

Table 4.2: Defined conditions of mode transition. (winter season)

Guards	Definition
$c11 : T_{out} \geq T_d + T_{thh}$	outside temperature is greater than desired temperature plus upper threshold value
$c12 : 0 \leq Q_{sseast} \leq 450 \ \&\& \ 0 \leq Q_{ssouth} \leq 150$	the heat gain from the solar radiation through the window glass from east and south position of the controlled room should be defined limits
$c2 : R_{ra} == 0$	No rain condition
$c3 : T_r \geq T_d + T_{thh}$	controlled room temperature is greater than the desired temperature plus its upper limit value
$c4 : T_r \leq T_d + T_{thl}$	controlled room temperature is less than the desired temperature plus its lower limit value

4.4.2 Parameters and Setup

Bedroom at second floor is used for simulation and experiments works. The bedroom has two small windows that face west and tow big windows that face north. These four windows are mounted with automatic open/closed motor. The windows are equipped

Figure 4.13: Curtain with automatic open/close motor.

Figure 4.14: Window with automatic on/off motor.

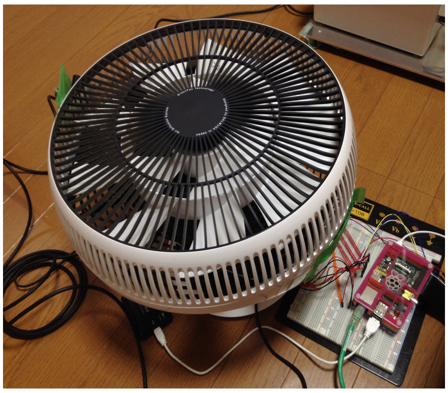


Figure 4.15: Stand fan with auto on/off.

with curtain which can be opened/closed automatically. One air-conditioner, a stand fan are also placed in the room. One sensor at each corner of floor and ceiling, and total 8 sensors are set experiment room. The actuators; air-conditioner, window, curtain and fan equipped in the room is shown in Figure 4.12 to 4.15. The peripheral elements installed in outdoor environment are depicted in Figures 4.22 to4.18. Parameters and setting for

Figure 4.16: Sensor for measuring outside temperature and solar radiation.

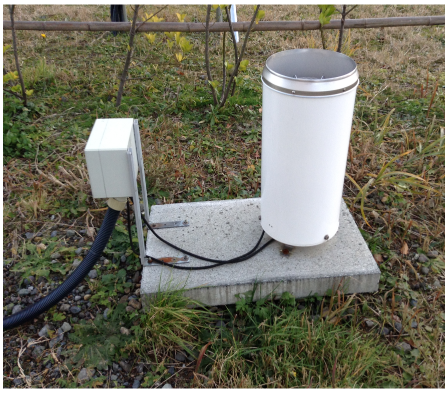


Figure 4.17: Sensor for measuring rain level.

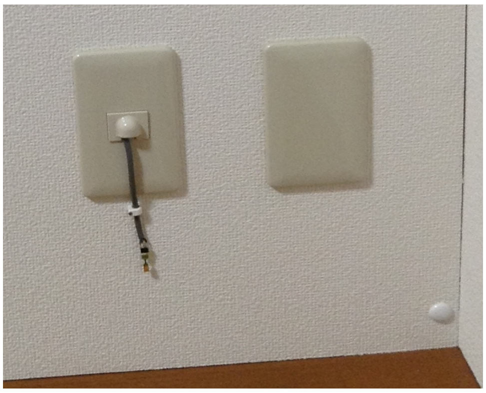


Figure 4.18: Sensor mounted on the corner of the wall.

simulation and experiments are expressed in Table 4.4.

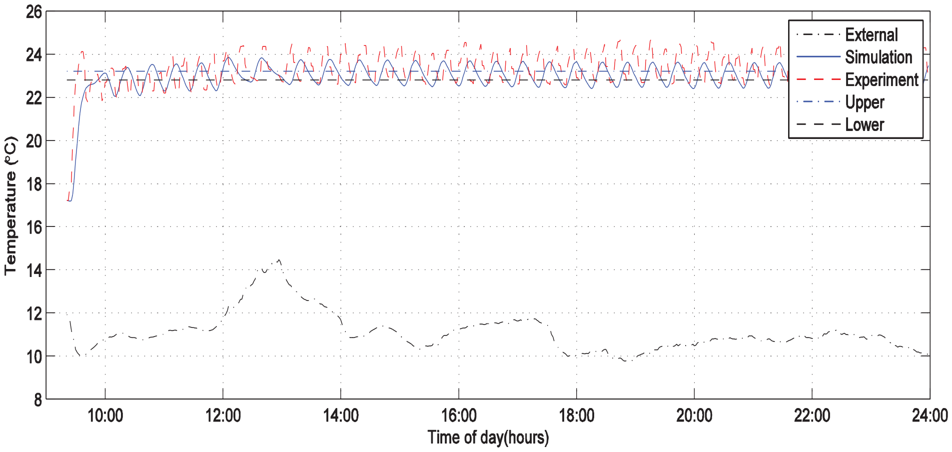


Figure 4.19: Simulation and experiment results of room temperature regulation.

4.4.3 Simulation and Experiment Results

This section presents the simulation and experiments results of room temperature with supervisory controller. The focus of this study is to evaluate the temperature control model proposed in Chapter 3 by comparing the simulation and experiment results. Figure 4.19 shows the simulation and experiment results of room temperature regulation. It observes that the error temperature between the simulation and experiment is not big and it ensures that the validation of proposed model. In this control scenario, the room temperature is controlled only air-conditioner since the outside temperature do not satisfied the defined condition in supervisory control for winter season since the necessary outdoor temperature for window opening defined in the algorithm is $23.3°C$.

4.5 Discussion

In this section, the problems of oscillation occurrence in room temperature regulation is discussed. In Chapter 3, controlling the room temperature with multiple actuators is presented. It is observed that even the room temperature is well controlled with multiple actuators within defined limits, the oscillation of room temperature is large (See Figures 3.9 in Chapter 3). It may be because of many reasons such as low performance of controllers, precision of simulators, large disturbance occurrence in physical world which makes the system tired out to keep the desired state. Another one of the possibility is

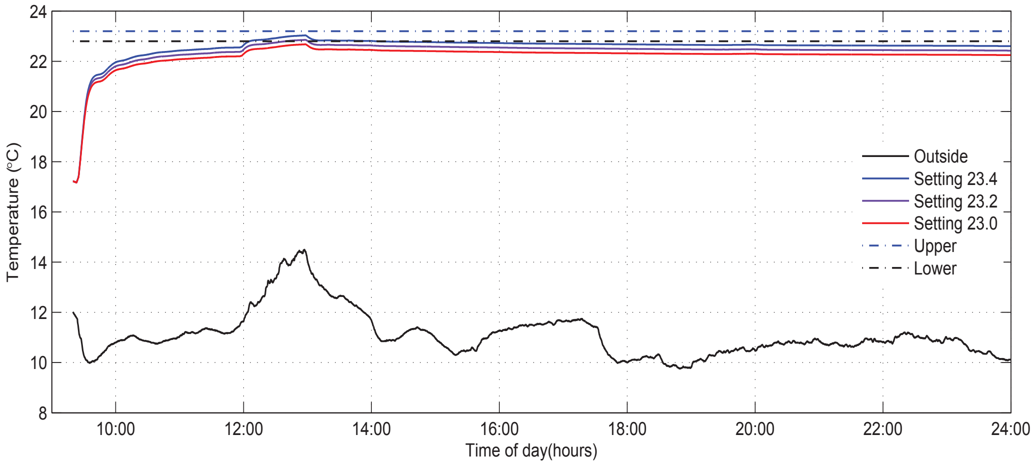


Figure 4.20: Room temperature changes according to different setting temperature.

because of the discrete nature of controller. With the best of my knowledge, I tried to remedy this problem by analysing the defined parameters in the system. The following shows the simulation results from the analysis of the system. All the simulations are conducted with the experiment data of winter season (05/12/2013) and the desired temperature is $23°C$.

1. Setting temperature variation

First simulation is concerned with the changing the setting temperature of air-conditioner. Figure 4.16 (a) show the variation of temperature with the setting temperature of $23.4°C$, $23.2°C$ and $23°C$. Under these setting temperature conditions, the oscillation is rarely occurs. The room temperature does not visit to demand limit except near 13:00 o'clock. It may be when the room temperature is near the margin point, it is difficult to keep it within the demand rang for the air-conditioner. The oscillation of temperature becomes large when the setting temperature is large, in Figure4.20 and Figure 4.21 , setting temperature with $24.5°C$ gives the most oscillation among three. Setting temperature with $23.5°C$ gives the lowest oscillation.

It observes that keeping the air-conditioner setting temperature close to the desired temperature, the oscillation of temperature will be decrease.

2. Desired temperature limits variation

Second study is related to changing the defined limits (upper and lower limits) of room temperature. Figure 4.22 shows the variation of room temperature with different defined limits. It can see that the oscillation is large when the range of defined limits small (e.g.,

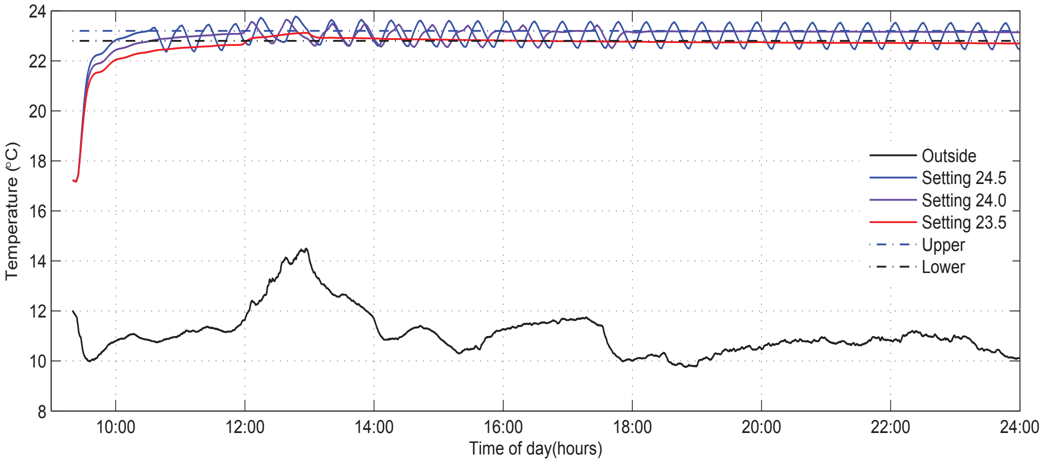


Figure 4.21: Room temperature changes according to different setting temperature.

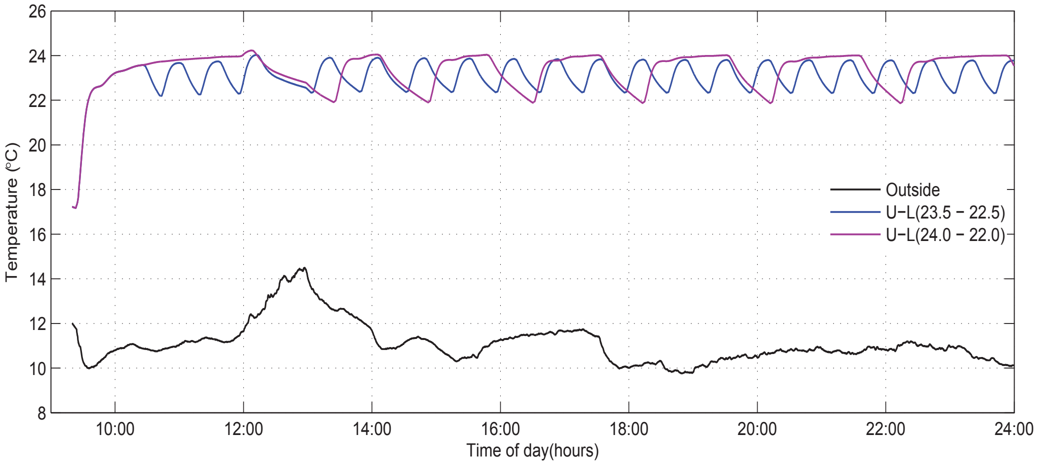


Figure 4.22: Room temperature changes with variation of upper and lower limit values.

defined limits with 23.5°C-22.5°C) and temperature oscillation is small with the defined limits with 24°C-22°C. Therefore, it can conclude that the temperature oscillation could be reduce by increasing the defined temperature limits.

3. Reducing the heating load of air-conditioner

Third simulation study is related to reducing the heating load of air-conditioner to observe the variation of room temperature. This study is done because we assume that if we reduce the heating load, the power of air-conditioning will be low. As results, temperature will not visit into the defined ranges and it will be around near the margin. It will reduce the frequent times of discrete control of air-conditioner. However, the air-conditioner designed in this thesis still can control the temperature within the defined limits even the

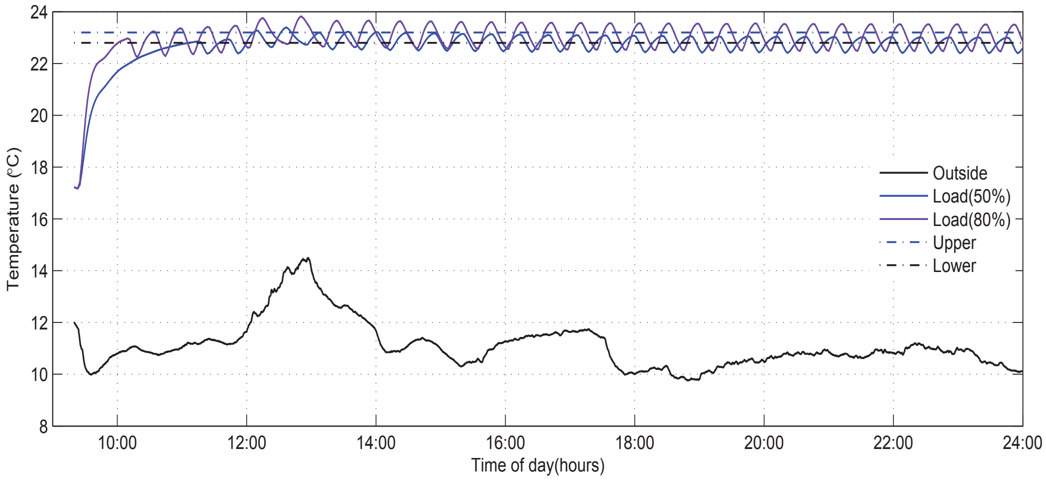


Figure 4.23: Room temperature changes with variation of upper and lower limit values.

heating load is reduced.

Nevertheless, the results show that the frequent of temperature oscillation is reduced in compare with the results presented in Chapter 3. Another observation from the Figure 4.18 is that settling time of temperature with reducing the heating load 50% (the usage of heating load is 50% over the full load) is slower than with reducing the heating load of 20% (the usage of heating load is 80% over the full load).

4.6 Summary

In this Chapter, the implementation of CPS-based temperature control system in real smart house, iHouse is presented. The analyzing of operation modes is also conducted. It will help the system designed to eliminate the modes that are not much effect the room temperature regulation and to observe the best conditions for defining the policies in supervisory controller. The validation of the system model is also verified by comparing the results from the simulation and experiments. Moreover, discussion on the temperature oscillation problems also done.

Table 4.3: Parameters and settings.

Parameter	*Definition*	*Value*
T_d	Desired temperature	$23°C$
T_{set}	Setting temperature of air-conditioner	$25°C$
T_{thh}	Upper limit value of desired temperature	$+0.2°C$
T_{thl}	Lower limit value of desired temperature	-$0.2°C$
T_r	Controlled room temperature	
T_{out}	Outside temperature	Input file from the measured raw data
$Q_{sseast}, Q_{sssouth}$	Heat gain from the solar radiation through the window glass from east and south position of the controlled room	Input file from the measured raw data
R_{ra}	The status of raining	Input file from the measured raw data
$Time_{wd}$	State holding time for window opening	30 minutes
$Time_{ac}$	State holding time for air-conditioning On	30 minutes
$Time_{ac2}$	The setting time to Off the air-conditioning once the room temperature arrives the upper limit of desired temperature	5 minutes
	Experiment date	05/12/2013
	Experiment time	9:00 to 24:00

Table 4.4: Transitions and their associated guards.

Transition	Transition condition
δ_{01}: mode $m0$ to mode $m1$	$c11$ & & $c12$ & & $c4$
δ_{06}: mode $m0$ to mode $m6$	$not(c11)$ & & $(not(c12) \Vert c12)$ $c4$ & & $not(c3)$ & & $(c6 \Vert not(c6))$
δ_{10}: mode $m1$ to mode $m0$	$c3$
δ_{12}: mode $m1$ to mode $m2$	$c11$ & & $c12$ & & $c2$ & & $c4$ & & $(c6 \Vert not(c6))$
δ_{16}: mode $m1$ to mode $m6$	$not(c11)$ & & $not(c12)$ $c4$ & & $not(c3)$ & & $(c6 \Vert not(c6))$
δ_{17}: mode $m1$ to mode $m7$	$c11$ & & $c12$ & & $not(c2)$ & & $not(c3)$ & & $(c6 \Vert not(c6))$
δ_{20}: mode $m2$ to mode $m0$	$c3$
δ_{26}: mode $m2$ to mode $m6$	$(timer > Time_{sh})$ & & $not(c11)$ & & $not(c12)$ $c4$ & & $not(c3)$ & & $(c6 \Vert not(c6))$
δ_{27}: mode $m2$ to mode $m7$	$(timer > Time_{sh})$ & & $c11$ & & $c12$ & & $not(c2)$ & & $c4$ & & $(c6 \Vert not(c6))$
δ_{60}: mode $m6$ to mode $m0$	$c3$
δ_{62}: mode $m6$ to mode $m2$	$c11$ & & $c12$ & & $c2$ & & $c4$ & & $(c6 \Vert not(c6))$
δ_{70}: mode $m7$ to mode $m0$	$c3$
δ_{72}: mode $m7$ to mode $m2$	$c11$ & & $c12$ & & $c2$ & & $c4$ & & $(c6 \Vert not(c6))$
δ_{76}: mode $m7$ to mode $m6$	$not(c11)$ & & $not(c12)$ $c4$ & & $(c6 \Vert not(c6))$

Chapter 5

A Particle Swarm Optimization Approach for Parameter Optimization of Mode Transition in Multi-mode Hybrid Automaton

5.1 Introduction

Recently, the integrated control systems with computing, communication and controlling for active interaction between physical (e.g. electronic equipment with embedded sensors) and cyber (computational) elements, called Cyber Physical Systems (CPSs), have gradually attracted more and more attention in a variety of different areas. In CPS, embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical process affect computations and vice versa. CPS is an integration of physical dynamics and computational systems, so they commonly combine both discrete and continuous dynamics [1]. Therefore modelling of cyber and physical processes can be viewed as hybrid system modelling. Continuous dynamics can be represented with differential equations and their corresponding actor models. For discrete dynamics, state machine is used.

CPSs are often required to satisfy certain operational goals such as safety, optimization a performance metric or controlling physical environment. Such kinds of system are usually composed of a set of actuators in which many processes are involved in satisfying the operational goal. Here, an actuator is defined as an object that performs corresponding actions according to received information to change the behaviour of the physical environment.

As an example, consider the room temperature control system in which the desired room temperature is adaptively and cooperatively controlled with multiple actuators (e.g. air-conditioner, window, fan, heater, etc.) to achieve the goal. Such adaptive behaviour of the system can be captured using a multi-mode automaton [81] modelling formalism. Each mode can be characterized by a unique set of tasks, resource constraints, and switching policies. Mode switches, or mode changes, reflect changes in the system or in the environment, which can be time-triggered or event-triggered [82].

Such kind of complex system can be composed of a collection of multi-modes that cooperate together to accomplish the goal. Consequently, as much as the number of modes increases, the probabilistic transitions between the modes increase as well. Moreover, it may be more than one operation modes that can satisfy the given specification. Or it may be one or more possible guards to transits the same mode. Therefore, it is desirable to find the optimal solution (transition mode or guards). At the same time, we need to consider on which condition the mode should be transits to another mode. As an example, consider an automated vehicle which wants to move to a target location. It might reach the target thorough the different paths, but it would be desirable to choose a path which minimizes fuel consumption. Or it might be different transition conditions (a set of guards) to move a target location, but it would be desirable to choose the optimal guard which minimize the cost.

In this chapter, a methodology that automatically prevent from visiting to unsafe (forbidden) modes from the original formulated system is presented. By this way, the numbers of transition as well as the useless modes are reduced and it provides a tighter abstraction of the system. Following this, the optimal values that are used for defining the constraint for mode transition is solved by using PSO approach. For example, in air-conditioning system, we need to define the condition (guard) for the transition of air-con Off mode to air-con ON mode. Here our interest is the values of the parameters defined in guard, i.e., air-con will turn off when the room temperature reaches $26°C$ or

$27°C$. Such kinds of parameters are optimized in CPS-based HTC system presented in this Chapter. The optimizer is implemented in real home environment simulator. In order to evaluate the system, a comparative study with the conventional systems in terms of energy, thermal discomfort and number of state transitions is carried out.

The rest of this chapter is organized as follows. Some state-of-the-art research works that are related to this chapter are summarized in Section 5.2. Preliminaries works in Section 5.3 and problem formulation in Section 5.4 are presented. The parameter optimization with PSO approach is described in Section 5.5. Simulation studies are presented in Section 5.6 and summarize the chapter in Section 5.7.

5.2 Related Works

To achieve low energy consumption in homes, it is critical to consider an advanced control algorithms. Energy consumption for HVAC systems has been widely discussed in the literature. Many researchers focused on mathematical models and simulation approaches. [83] and [84] proposed a supervisory control strategy to optimize the set points of local-loop controllers used in a multi-zone HVAC systems. Integrating building energy simulation software Energy Plus with a generic optimization program GenOpt, Djuric et al. [85] build a model to optimize parameters influencing energy, thermal comfort and investment cost. Mossolly et al. [86] examined optimal control strategies of a variable air volume air-conditioning system using a genetic algorithm. HVAC systems are complex, nonlinear and large-scale systems involving numerous constraints, and thus many studies focused on using data mining approaches to build predictive models.

Ari et al. [87] applied fuzzy logic and a neural network to approximate indoor comfort and energy optimization. Kusiak et al. [88] to [90] presented dynamic models to predict energy consumption and thermal comfort at current time and future time periods using neural network.

Application of Particle swarm optimization (PSO) in HVAC system can be found in [91],[92], [93] and [94]. [91] use PSO algorithm to tuning the PID parameters Kp, Ki, Kd. [92] propose a next-generation dynamic predictive model derived with data mining algorithm. This model is optimized with a strength multi objective particle-swarm optimization algorithm which is suitable for solving complex, nonlinear, discrete, and large-scale system. [93] applied PSO algorithm for the heating system planning problem. [94] developed and presented to optimally select both building envelop features and heating and air conditioning system design and operation settings. Moreover, they compare the effective of the three algorithms; Genetic algorithm, PSO algorithm and sequential search algorithm.

Unlike the existing researches, the application of PSO algorithm for parameter optimization of in mode transition (guard) for multi-mode hybrid automaton is presented in this chapter. The optimizer is implemented in real-house-based simulator. The advantages of PSO its simplicity and easy to implement as an evolution algorithm, the quick optimal search in multi-dimensional solution space. Moreover, the hybrid temperature control (HTC) system is non-linear system, and therefore it is preferable to apply PSO algorithm. PSO algorithm proposed in this chapter is to optimize the design parameters that have as significant effect on the heating and cooling thermal loads of buildings.

5.3 Preliminaries

In this section, a brief explanation of mathematical model of air-conditioned room, thermal simulator and the overview of PSO algorithm are introduced.

5.3.1 Mathematical Model of Air-conditioned Room

In this chapter, the temperature control of a room with three actuators; air-conditioner, window and curtain. Each actuator has discrete-valued control inputs of On/Off or Open/Close is considered. The same thermal model explained in Section 3.4, Chapter 3 is used. The number of operation modes, state transitions and their associated guards for room temperature control with three actuators and supervisory control is same as describe in Section 3.7.2, Chapter 3.

5.3.2 Thermal Simulator

Thermal simulator is a simulator which can simulate thermal environment of house. In this research, thermal simulator that is created based on the real house environment is employed and the evolution of thermal load is close to in real house. This simulator is applied to implement optimization algorithm and the details of simulator can be found in [66].

5.3.3 PSO

The PSO is proposed by Kennedy and Eberhart [95], [96] in 1995, and the motivation for the development of this algorithm was studied based on the simulation of simplified animal social behaviours, such as fish schooling and bird flocking. Similar to other population-based optimization methods such as genetic algorithms, the particle swarm algorithm starts with the random initialization of a population of particles in the search space [98]. However, unlike in other evolutionary optimization methods, in PSO there is no direct recombination of genetic material between individuals during the search. The PSO algorithm works on the social behaviour of particles in the swarm. Therefore, it provides the global best solution by simply adjusting the trajectory of each individual toward its own best location and toward the best particle of the entire swarm at each time step (generation) [[95], [99], [100]]. The PSO method is becoming very popular due to its simplicity of implementation and ability to quickly converge to a reasonably good solution.

Formulation of General PSO

Specifically, PSO algorithm maintains a population of particles, each of which represents a potential solution to an optimization problem. The position of the particle denotes a feasible, if not the best solution to the problem. The optimum progress is required to move the particle position in order to improve the value of objective function. The convergence condition always requires setting up the move iteration number of particle.

The position of particle move rule is shown as follows:

$$V_s(t+1) = \omega V_s(t) + C_1 r_1 (P_s - X_s(t)) + C_2 r_2 (G - X_s(t)) \tag{5.1}$$

$$X_s(t+1) = X_s(t) + V_s(t+1) \tag{5.2}$$

where $V_s(t)$ represents the velocity of particle s in t time; $X_s(t)$ represents the position vector of particle s in t time; P_s is the personal best position of particle s; G is the best position of the particle found at present; ω represents inertial weight; C_1 and C_2 are two acceleration constants, called cognitive and social parameters, respectively; and r_1 and r_2 are two random functions in the range [0,1].

5.4 Problem Formulation

Consider the system of multi-mode hybrid automaton. And assume that each actuator having only two discrete-valued control inputs (On/Off or Open/Close). As much as the number of modes increase the probabilistic transitions between the modes increase as well. In this aspect, the system need to avoid automatically for visiting the useless modes. The optimization problem consider in this chapter is to determine the optimal parameters for mode transition. These decision variables should be optimized for the energy consumption of heating and cooling devices, occupant's thermal discomfort and frequency of mode transition. The optimization problem is formulated through the determination of the problem variables, the objective functions, and the constraints.

Example

Consider the room temperature control system with three actuators; air-conditioner, window, and curtain. Each actuator has two discrete-valued control inputs (On/Off or Open/Close). Then the size of the state composition is 2^n=2^3=8 , where n is the number of actuators. Table 5.1 shows the operation modes associated with its actuators.

Variables for optimization

In this example, the system optimizes the values of the following parameters those are used for deciding the state transition.

T_{ac1}, T_{ac2}, T_{win1}, T_{win2}, T_{win3}, T_{win4}, T_{win5}, $solar1$, $solar2$, $solar3$, $solar4$, $T_{curtain1}$, $T_{curtain2}$
where

T_{ac1}: the value of temperature to turn On the air-con

T_{ac2}: the value of temperature to turn OFF the air-con

T_{win1}: temperature of the room to open the window

T_{win2}: outside temperature to open the window

T_{win3}: temperature of the room to close the window

T_{win4}: minimum outside temperature to close the window

T_{win5}: maximum outside temperature to open the window

Table 5.1: Operation modes associated with its actuators.

State	Air-conditioner	Curtain	Window
1	OFF	CLOSE	CLOSE
2	OFF	CLOSE	OPEN
3	OFF	OPEN	CLOSE
4	OFF	OPEN	OPEN
5	ON	CLOSE	CLOSE
6	ON	CLOSE	OPEN
7	ON	OPEN	CLOSE
8	ON	OPEN	OPEN

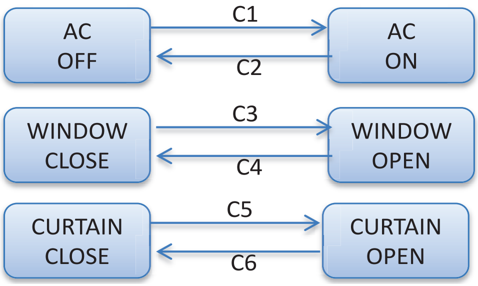


Figure 5.1: Original state transition.

$solar2$, $solar3$: the value of solar gain from the east and south sides to open the curtain

$solar3$, $solar4$: the value of solar gain from the east and south sides to close the curtain

$T_{curtain1}$: the value of outside temperature to open the curtain

$T_{curtain2}$: the value of outside temperature to close the curtain

Condition of original transitions

Figure 5.1 shows the original state transition of each actuator and Table 5.2 explains the transition conditions and their definition. For simplicity, the conditions for state transition are defined with general consideration. For example, the transition from air-conditioner Off to On state will happen when the condition C1; the room temperature is greater than the value of temperature to turn on the air-conditioner; is satisfied.

State composition and transition

Table 5.2: Transition condition and their definition.

Name	Transition name	Condition
C1	AC_{OFF-ON}	$T_{room} > T_{ac1}$
C2	AC_{ON-OFF}	$T_{room} < T_{ac2}$
C3	$WIN_{CLOSE-OPEN}$	$T_{room} > T_{win1} \& \& T_{out} < T_{win2}$
C4	$WIN_{OPEN-CLOSE}$	$T_{room} < T_{win3} \parallel T_{out} < T_{win4} \parallel T_{out} > T_{win5}$
C5	$CURTAIN_{CLOSE-OPEN}$	$Solar_{east} < solar1 \& \& Solar_{south} < solar2 \& \& T_{out} < T_{curtain1}$
C6	$CURTAIN_{OPEN-CLOSE}$	$Solar_{east} > solar3 \parallel Solar_{south} > solar4 \parallel T_{out} > T_{curtain2}$

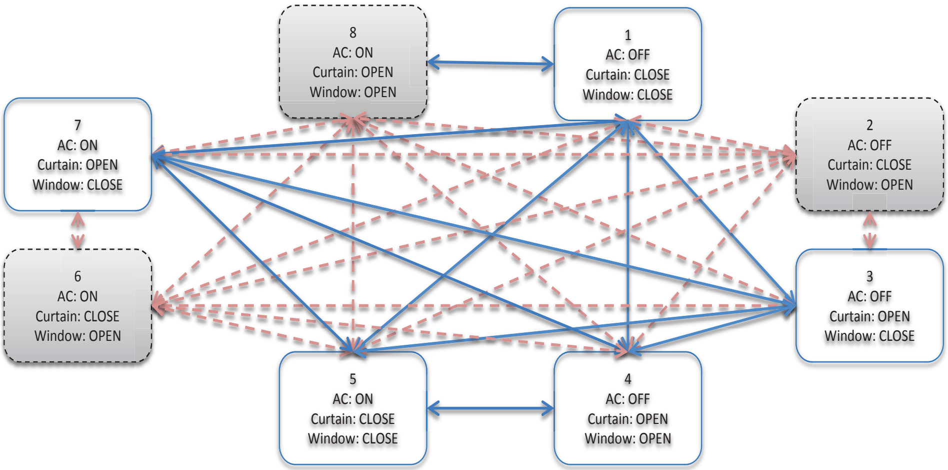
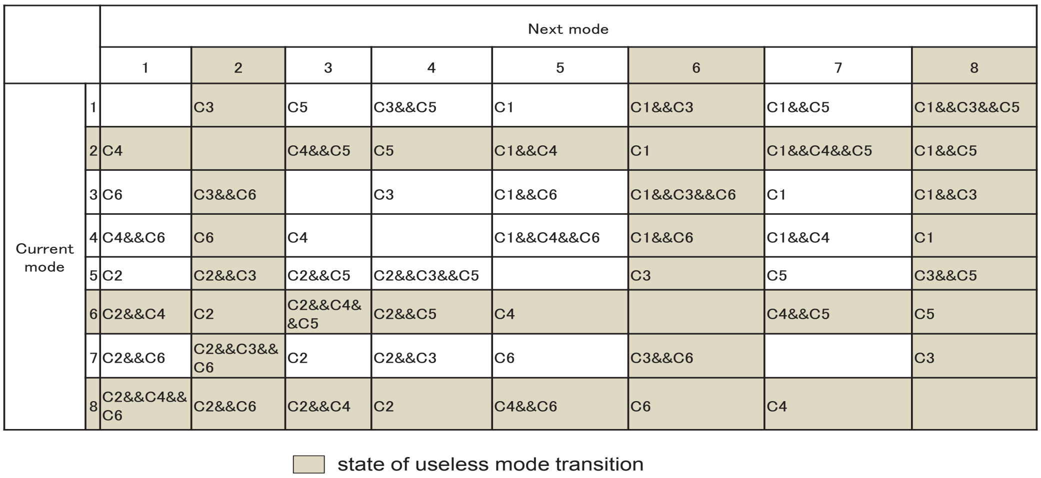


Figure 5.2: State transition and useless modes.

The system in Example has 8 modes of state combination. Figure 5.2 shows the transition between the states and the useless modes. Defined conditions (guards) for state transitions are explained in Figure 5.4. The highlighted modes are defined useless modes.

Prohibiting the visit to useless modes

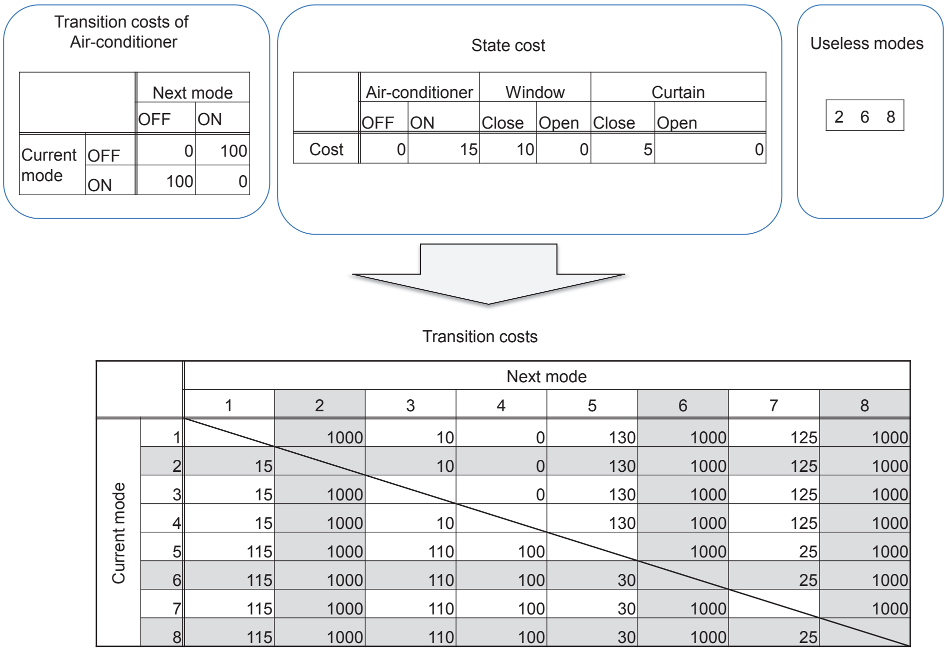
Modes $m2$,mode $m6$ and mode $m8$ are defined as useless modes in this chapter. Preventing the visit to those defined useless modes is designed in such away that each mode is associated with the cost for state and transition. Useless modes are assigned with the largest cost values and the rest modes are assigned according to the type of the actuator along with the knowledge of the designer. Then, the system will transits to the mode



Current mode	Next mode: 1	2	3	4	5	6	7	8
1		C3	C5	C3&&C5	C1	C1&&C3	C1&&C5	C1&&C3&&C5
2	C4		C4&&C5	C5	C1&&C4	C1	C1&&C4&&C5	C1&&C5
3	C6	C3&&C6		C3	C1&&C6	C1&&C3&&C6	C1	C1&&C3
4	C4&&C6	C6	C4		C1&&C4&&C6	C1&&C6	C1&&C4	C1
5	C2	C2&&C3	C2&&C5	C2&&C3&&C5		C3	C5	C3&&C5
6	C2&&C4	C2	C2&&C4&&C5	C2&&C5	C4		C4&&C5	C5
7	C2&&C6	C2&&C3&&C6	C2	C2&&C3	C6	C3&&C6		C3
8	C2&&C4&&C6	C2&&C6	C2&&C4	C2	C4&&C6	C6	C4	

▨ state of useless mode transition

Figure 5.3: Condition (guard) for state transition (higlighted columns are useless modes).



Transition costs of Air-conditioner

Current mode	Next mode: OFF	ON
OFF	0	100
ON	100	0

State cost

	Air-conditioner		Window		Curtain	
	OFF	ON	Close	Open	Close	Open
Cost	0	15	10	0	5	0

Useless modes

2 6 8

Transition costs

Current mode	Next mode: 1	2	3	4	5	6	7	8
1		1000	10	0	130	1000	125	1000
2	15		10	0	130	1000	125	1000
3	15	1000		0	130	1000	125	1000
4	15	1000	10		130	1000	125	1000
5	115	1000	110	100		1000	25	1000
6	115	1000	110	100	30		25	1000
7	115	1000	110	100	30	1000		1000
8	115	1000	110	100	30	1000	25	

Figure 5.4: Defining cost for useless modes.

that gives smallest cost. 5.5 shows the example of avoiding the visit to useless modes. For example, consider the transition of mode 1, transition cost of air-conditioner for On to Off state is 100 and the state cost of air-conditioner On status is 15. Therefore mode $m1$ will transits to mode $m3$ at next operation time. By this way, the system will never visit to useless modes since they always give the largest cost.

Objective function

The objective function of the temperature control system is to minimize the energy usage, the temperature variation, in other words, the value of thermal discomfort, and the transition of the states. Then, the total cost function is defined as follows;

$$J = w1 \times f_p + w2 \times f_t + w3 \times f_n \tag{5.3}$$

where, $w1$, $w2$ and $w3$ are the weight values and solved by using the Linear Programming. f_p, f_t, and f_n are the cost functions of power consumption, temperature difference and number of state transition. For simplicity, the simple calculation for the cost function is used.

The cost function f_p can be calculated by integral of power consumption of air-conditioner $P(t)$ as follows

$$f_p = \int_0^t P(t)dt \tag{5.4}$$

The cost function f_t can be calculated by integral of square of differential of room temperature (T_r) from the desired temperature (T_d) as follows

$$f_t = \int_0^t (T_d - T_r)^2 dt \tag{5.5}$$

The cost function f_n can be calculated by total number of transitions ($N_t rans$) as follows

$$f_t = \int_0^t N_{trans} \tag{5.6}$$

5.5 Parameter Optimization with PSO Approach

In this section, the formulation of PSO algorithm and the parameters that are considered in this chapter are presented. The procedure of PSO optimization is as follows.

Step 1: Initialize a swarm of n particles with random positions and velocities within the specified range. The initial swarm particles are initialized to 20 particles with random position and velocity. The points had been randomly selected in the possible range of the decision variables describe in Section 5.4.

The only task is to determine the exact values of decision variables. The optimal group of values that can make the system performance best should be selected. In this Chapter, PSO algorithm is applied to search the optimal values;T_{ac1}, T_{ac2}, T_{win1}, T_{win2}, T_{win3}, T_{win4}, T_{win5}, $solar_1$, $solar_2$, $solar_3$, $solar_4$, $T_{curtain1}$, $T_{curtain2}$ for state transition.

Step 2: For each particle, calculate the corresponding decision variables and the response of the control system, then, evaluate the fitness function.

Step 3: Compare particles fitness evaluation with its pbest, if current value is larger than pbest, then set pbest equal to the current value.

Step 4: Compare particle's fitness evaluation with gbest. If current value is larger than gbest, then set gbest equal to the current value.

Step 5: For each particle, change the velocity and position of the particle according to Equation 5.1 and 5.2. If the position of the particle is out of the specified range, produce new position and velocity randomly within the specified rang to replace the current one.

Step 6: If the number of iterations reaches the maximum, then stop. The latest gbest is regarded as the optimal decision variables. Otherwise, loop to step 2 until a maximum number of iterations is met.

5.6 Simulation Studies

5.6.1 Simulation Setups

In this section, the setting parameters for simulation and the simulation scenarios are explained. Table 5.3 shows the parameter and setting for PSO algorithm optimization for decision variables of state transitions. The raw measured data from experiment house, iHouse [21] are used as the input data for simulation. The library of PSO optimizer [101] is implemented in the simulation.

To evaluate the performance of the system which uses PSO optimization, a comparative study with the conventional controller (example 1 without PSO optimization), supervisory controller which is carefully designed by the designer (supervisory type 4,

Table 5.3: Parameters and setting for PSO algorithm.

Parameter	Value
particle	60
iterations	30
desired temperature	27 $^{\circ}C$
date of measured data used by simulator	2013/07/08
$w1$	0.234757
$w2$	0.00175447
$w3$	0.763489

SO4 described in Section 3.6.4, Chapter 3) and the controller designed with the PSO optimization algorithm (Example 1 with PSO optimization) are carried out.

5.6.2 Simulation Results

The optimal decision values given by the PSO optimization is shown in Table 4. The simulation results of room temperature control are shown in Figure 5.6. It is observed that the variation of room temperature with PSO is larger than supervisory control and the room temperature is mostly higher than desired temperature because of optimizing the parameters by minimizing the cost function. However, the temperature variation with supervisory control and conventional control is not much different.

In all three controllers, it seems that the room temperature is getting higher than defined limit. It is because of the defined transition condition in supervisory controller, i.e., the system will stay in window opening mode as long as outside environment condition is satisfied. However, the room temperature will increase because of the neighbouring room temperature and low outside air velocity. Figures 5.7 to 5.3 show the energy consumption, amount of temperature deviation for one day and the number of state transition under the

Table 5.4: Optima values given by PSO algorithm.

Parameter	Value
T_{ac1}	27.951
T_{ac2}	26.3645
T_{win1}	25.41
T_{win2}	27.361
T_{win3}	25
T_{win4}	30
T_{win5}	27.971
solar1	503.8
solar2	589.5
solar3	1000
solar4	1000
$T_{curtain1}$	26.444
$T_{curtain2}$	29.6215

three different controllers. In Figures 5.7 to 5.3, it can see that temperature control with PSO gives the lowest energy consumption and lowest number of transition times; on the other hand it gives the maximum value of temperature deviation for one day (Figure 5.8). Thus the temperature deviation is large under the PSO control. Moreover, the values of energy consumption and number of state transition with the supervisory control are larger than the other two controls. However the temperature is controlled within the defined limit with supervisory control. Therefore the trade-off between the energy consumption and regulation of desired temperature is observed.

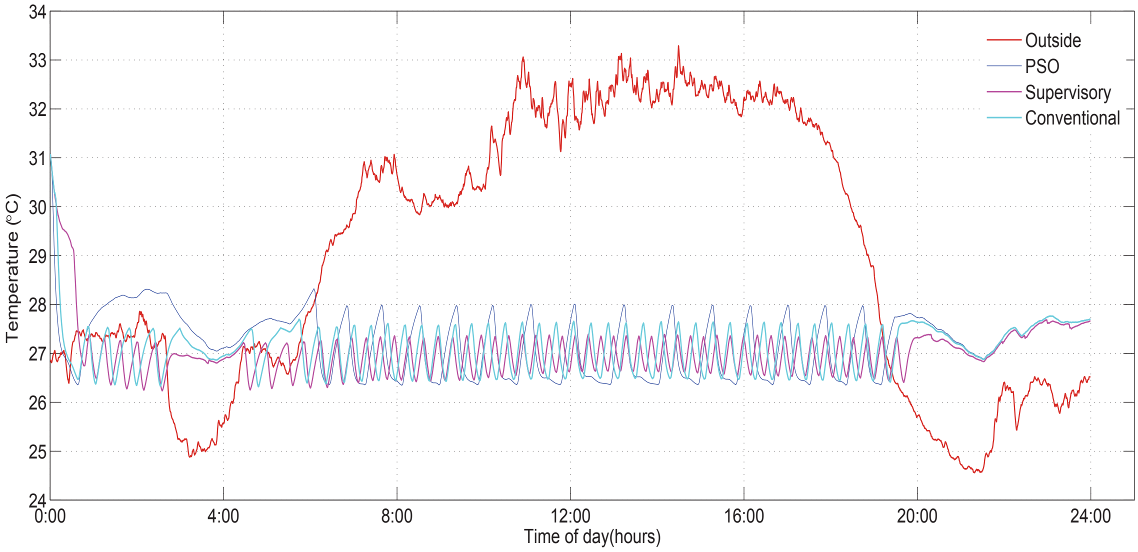


Figure 5.5: Temperature variation results comparison (2013/07/08).

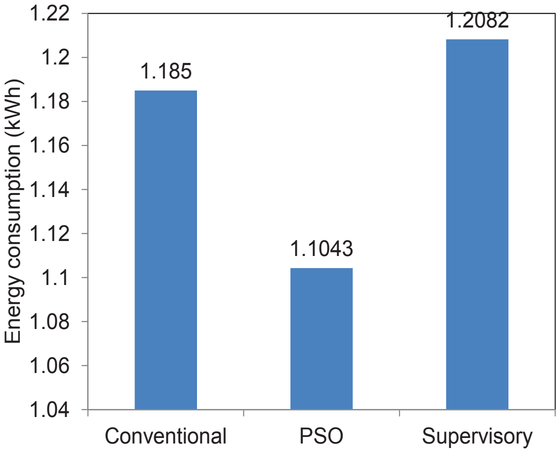


Figure 5.6: Energy comparison (2013/07/08).

5.7 Summary

In this chapter, the application of particle swarm optimization algorithm (PSO) for the parameter optimization of decision variables in multi-modes hybrid automation is presented. First the useless modes are defined to minimize the size (number) of the transitions between the modes. Following this the values of the parameters defined in mode transition (guard) are optimized by using PSO algorithm.

The performance of PSO is verified by conduction the simulation with real-house-based simulator and with measured data from the experiment house. The results show

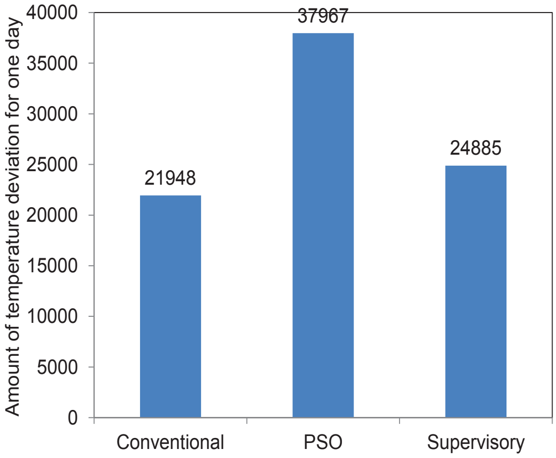


Figure 5.7: Amount of temperature deviation comparison (2013/07/08).

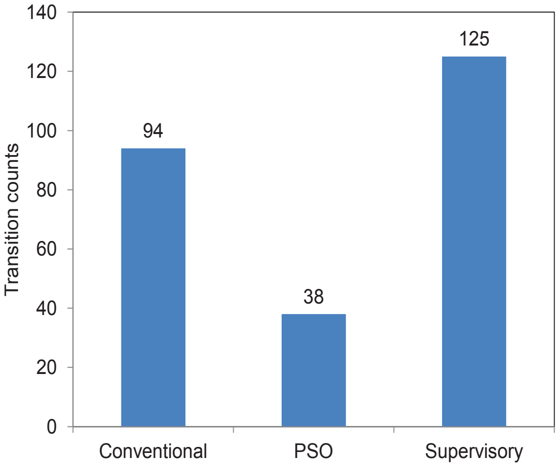


Figure 5.8: Number of state transitions comparsion (2013/07/08).

that PSO control gives better performance in the energy consumption and number of state transition times than the other two controllers. This study also addresses that PSO algorithm will be the best choice when we consider the system with non-linear nature and composition of multi-modes because of ease of implementation and simplicity. Comparative studies of other optimization algorithm for multi-modes hybrid automaton in terms of their simplicity and computation performance will be one of my future works.

Chapter 6

Computation Method for Model Predictive Control of Multiple Rooms Temperature Control System

6.1 Introduction

Control of large-scale systems is one of the fundamental problems in control engineering and it has been extensively studied so far [67] to [70]. From the viewpoint of total optimization, it is necessary to regard a set of individual systems as one system. In recent years, an energy management system such as smart grid [71], HEMS (Home Energy Management System) [72], [73], air-conditioning system [74], [75] becomes the important applications. The optimal control of an HVAC system with continuous-valued control input and discrete-valued control inputs can be regarded as a complex multi-variable problem. For example, in the multiple rooms' temperature control with many actuators as shown in Figure6.1, the output of air-conditioning system can be regarded as continuous-valued control input and ON/ OFF switches of ceiling fan can be regarded as discrete-valued control inputs. Therefore, it is necessary to consider the air-conditioning system with multiple actuators of both continuous-valued and discrete-valued control inputs. However, to my knowledge, such a large-scale system has not been directly considered so far. Furthermore, such a large-scale system can be considered as a class of hybrid systems and the finite-time optimal control problem is in general reduced to a mixed integer quadratic programming (MIQP) problem. However, the computation for MIQP is too long for such kind of large-scale systems and it is difficult to realize the model predictive control (MPC) method in which MIQP problem is solved every discrete time step.

To overcome this problem, [76] proposed the computational technique for two-layer MPC of large-scale systems with both continuous-valued control inputs and discrete-valued control inputs. In this method, the notation of virtual control input which is obtained by relaxing discrete-valued control inputs to continuous variables is introduced. In online computation, first, a continuous-valued control input and a virtual control input are calculated in the high-layer controller. By using the virtual control input, the MIQP problem is approximately rewritten as a quadratic programming (QP) problem, which can be relatively solved faster than MIQP problem. Next, using the virtual control inputs obtained, only a discrete-valued control input at the current time is calculated in the low-layer controller for each subsystem. This method solves the technical issue on the computation time. However, (i) quantization errors in the steady state, (ii) stabilization via MPC (i.e., stabilizing MPC), and (iii) applications have not been considered.

In this paper, the above three topics are considered as remaining issues. For (i), the cost function is improved under a certain assumption. For (ii), the stabilization MPC law is proposed based on the terminal constraint. For (iii), the proposed method is applied to air-conditioning systems. The results enhance the effectiveness of proposed method in MPC of large-scale systems.

The rest of this chapter is organized as follows. In section 6.2, research background related to this chapter is presented. Section 6.3 presents the problem formulation of large-scale system. The detail of computation method in Section 6.4 and the solution method in Section 6.5 are described. Section 6.6 presents the stabilizing model predictive control. Section 6.7 explains the application of proposed method in air-conditioning system. Section 6.8 shows our simulation settings and parameters and the numerical simulation results which shows the effectiveness of proposed method for solving the control problem of large-scale system. Finally, Section 6.9 summarizes the chapter.

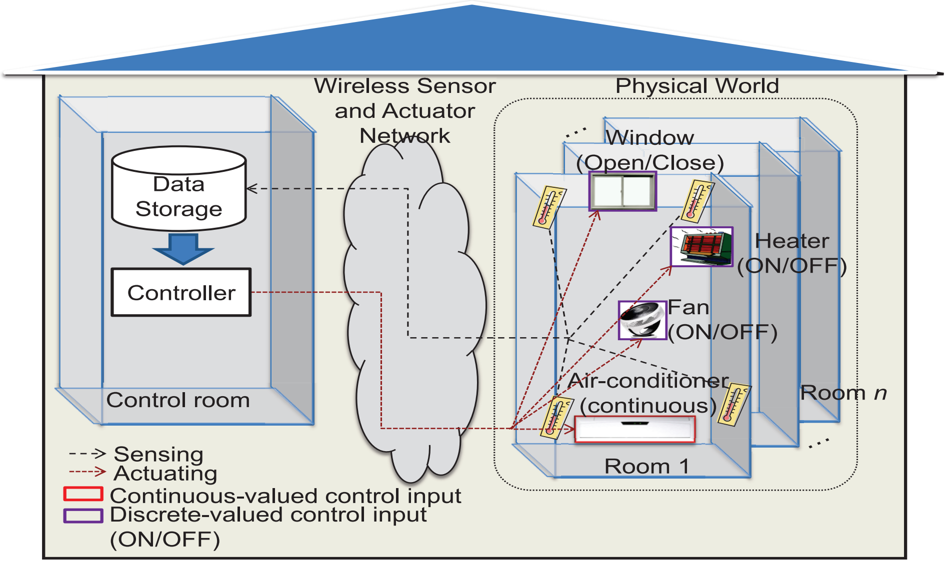


Figure 6.1: Temperature control of multiple rooms with continuous-valued input and discrete-valued inputs.

6.2 Related Works

Optimization is very important in various research fields of engineering and social science and it is used extensively in decision making. It is the process of finding an optimal or best solution to a problem usually subject to certain constraints or restrictions. Mathematical programming method is a methodology for solving optimization problems. It formulates a problem in the form of numerical formulas, and then applies a procedure that computes an optimal solution with respect to a given objective function.

There are numerous methods for solving optimization problems. However, not all the optimization problems can be solved efficiently with all the methods. The methods are different related to the problems and each method is designed with specific mathematical properties of the model. Thus, it is important to be able to identify the characteristics of the problem in order to find the correct method. The three kinds of entities are identified to formulae the optimization problem:

1. decision variables
2. objectives
3. constraints

A decision variable represents a choice that an optimization problem requires. For example, the decision consider for the system of this chapter is which operation modes have to operate (to reduce the energy).

An objective is some characteristic of an optimization problem that we want to minimize or maximize. In mathematical term, objectives are the functions of the decision variables. To find the optimum of the objective function means to determine the variables, such that, the objective function is either minimized or maximized.

A constraint is a restriction of decision variables in order to restrict the scope of a problem. For example, they may be forced to be non-negative or may not exceed a given value. These restrictions are represented in the form of equations known as constraint equations.

This following sub-section introduces the general definition of control algorithms: QP, MIQP and MPC that are considered in the formulation of the temperature control system problem of multiple rooms presented in this chapter.

6.2.1 Quadratic Programming (QP) problem

QP is one of the non-linear programming problems where the constraint equations are linear and the objective function is quadratic, non-linear. In particular, the objective function is a polynomial of the second degree. The general form of QP problem is formulated as follows:

$$minimize_x \qquad \frac{1}{2}x^T H x + f^T x \tag{6.1}$$

$$\text{subject to} \qquad A_\varepsilon x = b_\varepsilon$$

$$A_\tau x = b_\tau$$

where $x \in \mathbb{R}^n$, $H \in S^n_{(++)}$, $f \in \mathbb{R}^n$and the rows in $A_\varepsilon \in \mathbb{R}^{(m\times n)}$ are given by the vectors in $\{ a_i \in \mathbb{R}^n \mid i \in \varepsilon\}$ and the rows in $A_\tau \in \mathbb{R}^{(m\times n)}$ are given by the vectors in $\{ a_i \in \mathbb{R}^n \mid i \in \tau\}$. The column vectors b_ε and b_τ are analogously defined. The sets f, τ and ε are finite sets of indices. There are numerous methods for solving QP problems such as an active set strategy, and interior point algorithm.

6.2.2 Mixed Integer Quadratic Programming (MIQP) problem

MIQP is a special case of Mixed Integer Non-Linear Programming (MINLP). Generally, the MIQP problem looks similar to the ordinary QP problem. However, the important difference of MIQP against QP problem is that the optimization variables are not only allowed to be real valued, but also integer valued. A common special case of MIQP is when the integer variables are considered to be 0 or 1. To use a precise notation this problem is called a Mixed Binary Quadratic Programming (MBQP) problem. The standard notation for MBQP seems to MIQP. The mathematical definition of an MIQP problem is

$$minimize_{x \in \mathbb{R}^{n_c \times \{0,1\}_b^n}} \qquad \frac{1}{2} x^T H x + f^T x \tag{6.2}$$

$$\text{subject to} \qquad A_\varepsilon x = b_\varepsilon$$

$$A_\tau x = b_\tau$$

where $f \in \mathbb{R}^{(n_c+n_b)}$, $H \in S_+^{(n_c+n_b)}$. Further, let A_ε, A_τ, b_ε and b_τ be defined as in (6.1) with $n = n_c + n_b$.

There exists several methods for solving MIQP problems. The four most commonly used methods for these kinds of problems are,

- Cutting plane methods
- Decomposition methods
- Logic-based methods
- Branch and bound methods

Several authors claim that branch and bound is the best method for mixed integer programming. An important explanation in to why branch and bound is so fast is that the QP sub problems are very cheap to solve. This is not the case for general MINLP, where several QP problems have to be solved in each node in the branch and bond tree. In the MINLP case there exist important problem classes where branch and bound is not the best method.

There exists several software for solving MIQP problems. For MATLAB, free software like *miqp.m* can be used. Commonly used commercial software is CPLEX.

6.2.3 Model Predictive Control (MPC)

MPC is well-known control based on on-line optimization. However, the main limitation of MPC is its on-line computational complexity and it restricts its applicability to relatively slow and small problems. MPC has become the acceptable standard for complex constrained multi variable control problems in the process industries. In MPC, an open-loop optimal control problem is solved at each sampling time over a finite horizon and only the optimal control inputs at current time are applied to the plant. At the next time step, computation is repeated from the new state and over a shifted horizon.

The most commonly used variant of MPC is so-called linear MPC, where the dynamics is linear and a quadratic objective similar to the one used in Linear Quadratic (LQ) control is used. Linear/non-linear MPC is used different according to the linear/non-linear controlled system model. A discrete-time linear time-invariant model on state space form is given by

$$x(t+1) = Ax(t) + Bu(t) \tag{6.3}$$

$$y(t) = Cx(t) \tag{6.4}$$

where $t \in \mathbb{Z}$ is the discrete time, $x(t) \in \mathbb{R}^n$ is the state, $u(t) \in \mathbb{R}^m$ is the control input and $y(t) \in \mathbb{R}^p$ is the controlled output. The objective or performance measure, to minimize is a quadratic function like

$$J(t_0) = \sum_{s=0}^{N-1} (\| \, y(t_0+s) - r(t_0+s) \, \|_{Qe}^2 + \| \, u(t_0+s) \, \|_{Qe}^2) + \| \, y(t_0+N) - N \, \|_{Qe}^2 \tag{6.5}$$

where $Q_e \in \mathbb{S}_{++}^p$ and $Q_u \in \mathbb{S}_{++}^m$ and $r(t) \in \mathbb{R}^p$ is the reference signal. Often, the constraints are defined as

$$H_u(t)u(t) + H_x(t)x(t) + h(t) \leq 0 \tag{6.6}$$

In MPC, the future behaviour of the system is predicted N time steps ahead. In this context, prediction means that a system model like (6.3) is used to calculate how the system will react to control inputs and thereby what will happen in the future if a certain control input is applied to the system. Here, N is the prediction horizon which in practice is chosen long enough to cover a normal transient of the controlled system.

There are several different ways to model (6.3), (6.4) and (6.5) on the form of a formal optimization problem. If the system is linear and the objective is quadratic, the resulting optimization problem is a QP. Hence, the optimization problem for linear MPC is supposed easy to solve.

In order to get closed-loop control, the approach above is used in a receding horizon fashion, which means that the prediction interval is moved one step forward after each completed optimization. After the optimization has been performed, only the first control signal in the optimal control signal sequence computed is applied to the system and the others are ignored. In the next time step, a new optimization is performed and the procedure is repeated. Due to modelling errors and unknown disturbances, the predicted behaviour and the actual behaviour of the system do not usually completely coincide. Such errors are, if they are sufficiently small, handled by the feedback in the algorithm.

An extension to linear MPC is non-linear MPC. This extension handles non-linear systems and a general non-linear norm in the objective function. The resulting optimization problem is more difficult to solve in general. A special case of non-linear MPC is to handle systems described partly by logics. These are called hybrid systems and provide a unified framework for describing processes evolving according to continuous dynamics, discrete dynamics and logic rules.
Algorithm 6.1 Basic MPC controller:

1. Set $t = 0$, and give the current state $x(t) = x_t$.

2. Solve equation (6.4).

3. Apply only $u(t)$ to the plant

4. Set t:=t+1, measure $x(t)$, and return to step 2.

6.3 Problem Formulation

In this Chapter, the discrete-time large-scale system consisting of s subsystems is considered and its equation is given by

$$\Sigma_i : x_i(k+1) = \sum_{j=1}^{s} A_{ij} x_j(k) + B_i^c u_i^c(k) + B_i^d u_i^d(k) \tag{6.7}$$

where i=1,2,... ,s , and k=0,1,2,... is the discrete time. $x_i(k) \in R^{(}n_i)$ is the state in the subsystem i. $u_i^c(k) \in U_i^c \subseteq R^{m_i^c}$ and $u_i^d(k) \in R^{m_i^d}$ are the continuous-valued control input and the discrete-valued control input in the subsystem i, respectively. $\mathcal{U}_i^c$ is given as a closed convex set. $u_i^d(k)$ is given by

$$u_i^d(k) = \begin{bmatrix} u_{i,1}^d(k) \\ u_{i,2}^d(k) \\ \vdots \\ u_{i,m_i^d}^d(k) \end{bmatrix},$$
$$u_{i,l}^d(k) \in \left\{ u_{i,l,1}^d, u_{i,l,2}^d, \ldots, u_{i,l,p_{i,l}}^d \right\} =: \mathcal{U}_{i,l}^d \subseteq \mathcal{R}^1$$

where $\mathcal{U}_{i,l}^d$ is the finite set expressing the candidates of the l-th element of the discrete-valued control input in the subsystem i. The number of elements of $\mathcal{U}_{i,l}^d$ is given as $p_{i,l}$. In the system (6.7), the pair $(A_{ii}, [B_i^c \ B_i^d])$ expresses the dynamics of the subsystem i, and the matrices $A_{ij}, i \neq j$ express the effect of other subsystems j, $i \neq j$.

Since the system Σ_i has both the continuous-valued control input and the discrete-valued control input, the system Σ_i can be regarded as a class of hybrid systems. Hereafter, let Σ denote the large-scale system consisting Σ_i, $i = 1, 2, \ldots, s$.

First, the MIQP problem is formulated. Then, the optimal control problem of large-scale system $\sum$ is considered and defined

$$x(k) := \left[\ x_1^T(k) \ \ x_2^T(k) \ \ \cdots \ \ x_s^T(k) \ \right]^T,$$
$$u_i(k) := \left[\ (u_i^c(k))^T \ \ (u_i^d(k))^T \ \right]^T,$$
$$u(k) := \left[\ u_1^T(k) \ \ u_2^T(k) \ \ \cdots \ \ u_s^T(k) \ \right]^T.$$

Then the following problem is considered.

Problem 1:

Suppose that for the large-scale system $\sum$, the current state $x(t) = x_t$ is given, where t is the current time. Then, find both continuous-valued and discrete-valued control inputs $u(k)$, $k = t$, $t + 1, \cdots, t + N - 1$ by minimizing the following cost function

$$J = \sum_{k=t}^{t+N-1} \{\hat{x}^T(k) Q \hat{x}(k) + u(k)^T R u(k)\} + \hat{x}^T(t+N) Q_f \hat{x}(t+N) \tag{6.8}$$

where $\hat{x}(k) := x(k) - x_d$, and $Q, Q_f \geq 0$, and $R > 0$ are weighting matrices. The vector x_d is the desired state.

By assigning a binary variable to each element of $\mathcal{U}_{i,l}^{d}$, the subsystem Σ_i can be rewritten as a mixed logical dynamical (MLD) system [77]. Therefore, Problem 1 can be rewritten as a mixed integer quadratic programming (MIQP) problem. In the obtained MIQP problem, the dimension of continuous variables and that of binary variables are $\sum_{i=1}^{s} m_i^c N$ and $\sum_{i=1}^{s}\sum_{l=1}^{m_i^d} p_{i,l}N$, respectively.

On the other hand, the finite-time optimal control problem is frequently used in model predictive control (MPC). In MPC, Problem 1, i.e., the MIQP problem must be solved at each time. However, in large-scale systems Σ, it is hard to solve Problem 1 within the practical computation time. Thus, it is necessary to consider a new method for solving Problem 1 under the situation that Problem 1 is used in MPC.

6.4 Computational Method in [76]

In this section, first, the outline of the proposed method in [76] is explained. Next, the notation of virtual control inputs [76] is explained. Finally using the virtual control inputs, a solution method for Problem 1 is derived.

6.4.1 Outline

For large-scale systems $\sum$, it is in general difficult to solve Problem 1 within the practical computation time. Here, the problem focus on the fact that in MPC, only $u(t)$ is applied to the plant. From this fact, if the state at $k = t, t+1, \ldots, t+N$ can be appropriately evaluated, then computation of the discrete-valued control input at $k = t$, $t+1$,…, $t+N$ is not required. In this Chapter, relaxing the discrete-valued control input at $k = t$, $t+1$, …, $t+N$ to a continuous variable, which is called here a virtual control input is considered. In the proposed procedure of MPC [76], first, a continuous-valued control input and a virtual control input is found by minimizing the cost function. Next, only discrete-valued control input at $k = t$ is derived.

Furthermore, in the hierarchical implementation of the proposed procedure of MPC, we consider both the high-layer centralized controller and the low-layer decentralized controller (see also Figure6.2). In the high-layer centralized controller, the continuous-valued control input and the virtual control input are computed. In each low-layer decentralized

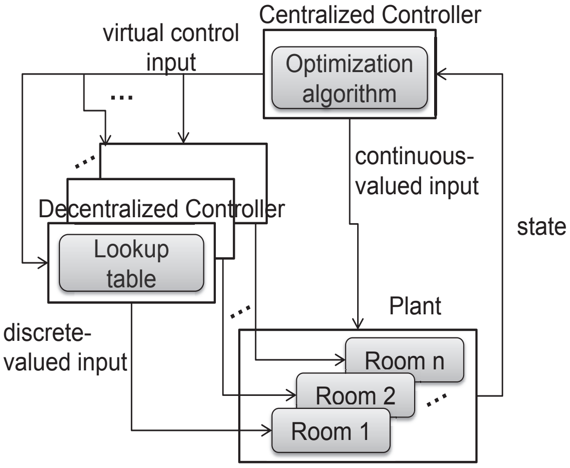


Figure 6.2: Large-scale control system.

controller, the discrete-valued control input at $k = t$ is computed using the virtual control input at $k = t$. Thus the computation load is decentralized.

The implementation of the proposed procedure of MPC with both centralized and decentralized controllers is shown in Figure 6.2. Hereafter, in this section, first, the notation of the virtual control input will be formally defined. Next, an approximate solution method of Problem1 will be derived. Finally the proposed procedure of MPC will be shown.

6.4.2 Virtual Control Input

The matrix B_i^d in the subsystem (6.7) is rewritten as

$$B_i^d = S_i \begin{bmatrix} I_{r_i} & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} T_i^1 \\ T_i^2 \end{bmatrix} \tag{6.9}$$

where $r_i := \text{rank} B_i^d \leq m_i^d$. Then, instead of the subsystem (6.7), the following subsystem is considered

$$\Sigma_i' : \; x_i(k+1) = \sum_{j=1}^{s} A_{ij} x_j(k) + B_i^c u_i^c(k) + B_i^v u_i^v(k) \tag{6.10}$$

where $B_i^v = S_i[\; I_{r_i} \;\; 0 \;]^T$. The vector $u_i^v(k) \in \mathcal{U}_i^v \subseteq \mathcal{R}^{r_i}$ is the r_i-dimensional continuous-valued control input. The set $\mathcal{U}_i^v$ is given as $\mathcal{U}_i^v = [\underline{u}_i^v, \overline{u}_i^v]$. The vector $\underline{u}_i^v$ ($\overline{u}_i^v$) is given as the value of the vector $T_i^1 u_i^d(k)$ such that each element of $T_i^1 u_i^d(k)$ is minimized (maximized), and can be derived from the finite set $\mathcal{U}_{i,l}^d$. Hereafter, $u_i^v(k)$ is called a *virtual control input*. It remark that the discrete-valued control input and the virtual control input are not one-to-one correspondence. The formulation of virtual control input is shown with one example.

Example 1: Suppose that $B_i^d u_i^d(k)$ in the subsystem (6.7) is given as

$$B_i^d u_i^d(k) = \begin{bmatrix} -1 & 1 & 2 \\ 1 & -1 & 1 \end{bmatrix} \begin{bmatrix} u_{i,1}^d(k) \\ u_{i,2}^d(k) \\ u_{i,3}^d(k) \end{bmatrix}$$

where $u_{i,1}^d(k) = \{0, 1, 2\} =: \mathcal{U}_{i,1}^d, u_{i,2}^d(k) = \{0, 2, 4\} =: \mathcal{U}_{i,2}^d, u_{i,3}^d(k) = \{0, \pm 3, \pm 5, \pm 7\} =: \mathcal{U}_{i,3}^d$. Noting here that $\mathrm{rank} B_i^d = 2$ holds, $B_i^d u_i^d(k)$ can be rewritten as

$$B_i^d u_i^d(k) = \begin{bmatrix} -1 & 2 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} u_{i,1}^d(k) - u_{i,2}^d(k) \\ u_{i,3}^d(k) \end{bmatrix}$$

Thus the following derivation is obtained

$$B_i^v u_i^v(k) = \begin{bmatrix} -1 & 2 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} u_{i,1}^v(k) \\ u_{i,2}^v(k) \end{bmatrix}$$

In addition, the constraint for virtual control inputs $u_{i,1}^v(k)$ and $u_{i,2}^v(k)$ is given as

$$\underbrace{\begin{bmatrix} -4 \\ -7 \end{bmatrix}}_{\underline{u}_i^v} \leq \begin{bmatrix} u_{i,1}^v(k) \\ u_{i,2}^v(k) \end{bmatrix} \leq \underbrace{\begin{bmatrix} 2 \\ 7 \end{bmatrix}}_{\overline{u}_i^v}$$

which can be computed from the finite sets $\mathcal{U}_{i,1}^d$, $\mathcal{U}_{i,2}^d$ and $\mathcal{U}_{i,3}^d$. ***Remark 1*:** Many actuators are included in each subsystem. In the example of air-conditioning systems, ceiling fans, local heaters, windows, and so on can be considered. In many cases, these correspond to discrete-valued control inputs, and the number of these may be greater than the dimension of the state. Thus in derivation of virtual control inputs, m_i^d to r_i is reduced.

6.5 Proposed Solution Method

In this section, first, consideration the effect of quantization errors, a solution method for Problem 1 is proposed. Next, the stabilization method via MPC is proposed.

6.5.1 Solution Method Consideration the Effect of Quantization Errors

The control system with discrete-valued control inputs, quantization errors may occur. In particular, quantization errors in the near-steady-state are important from the viewpoint of stabilization. In the case where the optimal control input in Problem 1 is applied to the plant, these errors may not occur, because the continuous-valued control input compensates these errors (more precisely, Assumption 1 below must be satisfied).

On the other hand, Problem 1 is approximately reduced to quadratic programming (QP) problem by replacing the discrete-valued control input with the virtual control input [76]. Then, the continuous-valued control input obtained by solving the approximated problem does not compensate quantization errors in general, because the virtual control input is used. To overcome this issue, the pair of continuous-valued and discrete-valued control inputs such that the state stays in the desired state (i.e., the steady state) are computed. For the cost function in the approximated problem the obtained pair is imposed as the desired control input.

It remark here that in the case where Problem 1 is solved, this pair is obtained in the steady state. From this fact, the above improvement of the cost function is also effective from the viewpoint of optimality. First, the following assumption is made for the desired state x_d in Problem 1. ***Assumption 1***: The desired state x_d is an equilibrium point of the large-scale system $\sum$. That is, there exists a control input u_d satisfying $x(k) = x_d$ and $(k+1) = x_d$.

The problem of finding u_d is reduced to the following mixed integer linear programming problem: find $u(k) = u_d$ by minimizing $u_d^T R u_d$ subject to the large-scale system $\sum$, $x(k) = x_d$ and $x(k+1) = x_d$. Hence, this can verify in off-line if the large-scale system $\sum$ satisfies Assumption 1. Define u'_d block-diag $(T_1^1, T_2^1, \cdots, T_s^1)u_d$. In addition, define

$$u'_i(k) := \left[\begin{array}{cc} (u_i^c(k))^T & (u_i^v(k))^T \end{array}\right]^T,$$

$$u'(k) := \left[\begin{array}{cccc} (u'_1(k))^T & (u'_2(k))^T & \cdots & (u'_s(k))^T \end{array}\right]^T$$

Then consider the following finite-time optimal control problem, instead of Problem 1.

Problem 2: Suppose that for the large-scale system consisting of subsystems $\sum'_i, i = 1, 2, \cdots, s$, the current state $x(t) = x_t$ is given, where t is the current time. Then find both continuous-valued and discrete-valued control inputs $u'_k, k = t, t+1, \cdots, t+N-1$ by minimizing the following cost function

$$J' = \sum_{k=t}^{t+N-1} \{\hat{x}^T(k)Q\hat{x}(k) + \hat{u}^T(k)R'\hat{u}^T(k)\} + \hat{x}^T(t+N)Q_f\hat{x}(t+N) \tag{6.11}$$

where $\hat{u}(k) := u'(k) - u'_d$, and R' is the weighting matrix obtained from the weighting matrix R in Problem 1 and the matrix T_i^1 in Equation (6.8).

Using the cost function J' with u'_d, the continuous-valued control input, which compensate the quantization errors in the steady state. More precisely, stability of the closed-loop system must be guaranteed and this is showed with a numerical example in Section 6.6. In the case that u'_d is not used, the effect of quantization errors may not be considered.

Since the decision variable in Problem 2 is only a continuous-valued variable, Problem 2 can be rewritten as a quadratic programming (QP) problem, which can be solved by a suitable solver such as IBM ILOG CPLEX Optimizer [78]. The dimension of decision variables is given by $\sum_{i=1}^{s}(m_i^c + r_i)N$.

The procedure for rewriting Problem 2 as a QP problem is same as that in the case in Problem 1. In addition, from the definition of the virtual control input; it shows that the minimum value of the cost function in Problem 2 gives the lower bound of the minimum value of the cost function in Problem 1.

By solving Problem 2, the virtual control input is obtained. From the obtained virtual control input, a discrete-valued control input can be obtained by the table look-up method in which a look-up table is generated off-line. The detail of formulating look-up table is shown in Section 6.8.

The proposed solution method for Problem 1 can be regarded as a method in which the MIQP problem corresponding to Problem 1 is divided into one QP problem (Problem 2) and s look-up tables for each subsystem. Problem 2 can be in general solved faster than Problem 1, and only the discrete-valued control input at $k = t$ is found by using look-up tables. From these observations, the computation time of the proposed solution method is smaller than that of one MIQP problem.

6.5.2 Proposed Procedure of Model Predictive Control Law

Finally, the procedure of MPC combining centralized control with decentralized control is summarized. The proposed procedure of MPC is as follows:

Step 1: Set $t = 0$, and give the current state $x(t) = x_t$.

Step 2: In the high-layer centralized controller, find both a continuous-valued control input and a virtual control input by solving Problem 2.

Step 3: Send the optimal values of both a continuous-valued control input and a virtual control input form the centralized controller to each low-layer decentralized controller.

Step 4: In each low-layer decentralized controller, find a discrete-valued control input at t.

Step 5: Apply only the control input at t to the plant.

Step 6: Set t:=t+1, measure $x(t)$, and go to Step 2.

6.6 Stabilizing Model Predictive Control

In this section, a discussion the stabilization via MPC (stabilizing MPC) is made. In stabilizing MPC, the following methods are known:

1. The constraint condition on the Lyapunov function, i.e., $x(k+1) \leq \rho V x(k)$, is imposed for the system $\sum$, where $V(x)$ is a non-negative function, and $\rho \in [0, 1)$ is a constant (see e.g.,[79]).
2. The terminal constraint condition $x(t+N) = x_d$ or $x(t+N) \in \mathcal{W}$ is imposed for the system $\sum$, where $\mathcal{W}$ is a positive invariant set (see, e.g., [77], [80]).

Here, the method (ii) is adopted, because in the method (i), it may be hard to guarantee the feasibility. Then, the following procedure of stabilizing MPC is proposed.

Procedure of Stabilizing MPC:

Step 1: Set $t = 0$, and give the current state $t = x_t$.

Step 2: Solve Problem 2 with the terminal constraint $(t+N) = x_d$.

Step 3: Find a discrete-valued control input at $k = t, t+1, \cdots, t+N$ using the table look-up method.

Step 4: For the fixed discrete-valued control input, solve Problem 1 with the terminal constraint $x(t+N) = x_d$.

Step 5: Apply only $u(t)$ to the plant.

Step 6: Set $t =: t+1$, measure $x(t)$, and return to Step 2.

After the discrete-valued control input at $k = t, t+1, \cdots, t+N$ is derived, the continuous-valued control input is derived. Hence, the hierarchical structure in Figure 6.2 cannot be applied to the above procedure. Since Problem 1 in Step 4 is a QP problem, in the above procedure, a QP problem must be solved twice at each time. The computation time of two QP problems is relatively smaller than that of one MIQP problem. According to the existing results in stabilizing MPC (see e.g., [77], [80]), obtain the following theorem can obtain immediately.

Theorem 1: The closed-loop system of Σ is asymptotically stable, i.e., $lim_{k\to\infty}x(k) = x_d$ if in the above procedure, Problem 2 in Step 2 and Problem 1 in Step 4 are feasible at $t = 0$. If the lower and upper bounds of quantization errors can be estimated, then instead of $(t+N) = x_d$, the constraint $x(t+N) \in \mathcal{X}(t+N) \subseteq \mathcal{W}$ may be imposed for the system, where $\mathcal{X}(k)$ is the set of the state at time k. The interval model proposed in [76] may adopt and, which is an over-approximation of the set $\mathcal{X}(k)$.

6.7 Application to Air-Conditioning Systems

In this section, the method explained in the Section 6.5 is applied to air-conditioning systems. First, the simple model of air-conditioning systems for multiple-rooms is derived.

6.7.1 Temperature Model for Many Rooms

First, the simple model of rooms' temperature control system with multiple actuators is formulated. The dynamics of temperature in room i can be expressed with the following first-order plus time delay model:

$$P_i(s) = \frac{K_i}{1+T_i s}e^{-Ls} \qquad (6.12)$$

where K_i, T_i and L are the static process gain, the time constant, and the time delay, respectively. For simplicity of discussion, the value of time delay L does not depends on room i. From Equation (6.12), the following state equation can be obtained

$$\begin{cases} \dot{q}_i(t) = -\frac{1}{T_i}q_i(t) + \frac{K_i}{T_i}u_i(t-L), \\ y_i(t) = q_i(t) \end{cases} \tag{6.13}$$

where q_i is the state that implies the temperature in one room, and u_i is the continuous-valued control input that implies, e.g. the output of a heat pump. Hereafter, the output equation $y_i(t) = q_i(t)$ is omitted.

Next, consider transforming (6.13) into a discrete-time system. For simplicity of discussion, suppose that the sampling period is given by L. Of course, the other value may be used. Then the following discrete-time linear system can obtain.

$$\begin{aligned} q_i(k+1) &= e^{-L/T_i}q_i(k) + \int_0^L e^{-\tau/T_i}\frac{K_i}{T_i}d\tau u_i(k-1) \\ &= e^{-L/T_i}q_i(k) + K_i(1-e^{-L/T_i})u_i(k-1). \end{aligned}$$

By defining $v_i(k) := u_i(k-1)$, we can obtain

$$\begin{bmatrix} q_i(k+1) \\ v_i(k+1) \end{bmatrix} = \begin{bmatrix} e^{-L/T_i} & K_i(1-e^{-L/T_i}) \\ 0 & 0 \end{bmatrix} \begin{bmatrix} q_i(k) \\ v_i(k) \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u_i(k).$$

Furthermore, the three kinds of discrete-valued inputs are considered as follows: (i) $u_i^w \in 0, 1$: Window (close/open), (ii) $u_i^h \in 0, 1, 2$: Local heater (off/low/high), (iii) $u_i^f \in 0, 1, 2$: Ventilation fan (off/low/high). The continuous-valued control input u_i^a is also added, and is called here an auxiliary continuous-valued input. Suppose that u_i^a is weal control, but the temperature can be changed instantaneously by u_i^a. Then the following temperature model in room i can obtain.

$$x_i(k+1) = A_i x_i(k) + B_i^c u_i^c(k) + B_i^d u_i^d(k)$$

where

$$x_i(k) := \begin{bmatrix} q_i(k) & v_i(k) \end{bmatrix}, u_i^c(k) := \begin{bmatrix} u_i(k) \\ u_i^a(k) \end{bmatrix}, u_i^d(k) := \begin{bmatrix} u_i^w(k) & u_i^h(k) & u_i^v(k) \end{bmatrix},$$

$$A_i := \begin{bmatrix} e^{-L/T_i} & K_i(1-e^{-L/T_i}) \\ 0 & 0 \end{bmatrix}, B_i^c := \begin{bmatrix} 0 & b_i^a \\ 1 & 0 \end{bmatrix}, B_i^d := \begin{bmatrix} b_i^w & b_i^h & b_i^v \\ 0 & 0 & 0 \end{bmatrix}$$

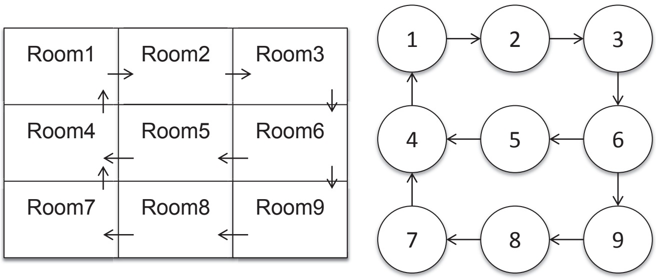


Figure 6.3: Example of multiple rooms. (left) Illustration. (right) Directed graph.

where $b_i^a \geq 0$, $b_i^w \leq 0$, $b_i^h \geq 0$ and $b_i^f \leq 0$ are constants, and are given in advance. Assume that outside temperature is equal to or less than room temperature.

Finally, the effect of other rooms are also considered. Assume that the airflow between the rooms is expressed as a directed graph, Figure 6.3. For example, the room 1 has an effect from room 4; room 4 has an effect from room 5 and room 7, and so on. In addition, room 5 has no window, that is, $b_5^w = 0$ holds. Then, the coupled term from room i to room j can be obtained as

$$A_{ji}(x_i(k) - x_j(k)), A_{ji} := \begin{bmatrix} a_{ji} & 0 \\ 0 & 0 \end{bmatrix}$$

where $a_{ji} \geq 0$ is a constant that express the effect level. From Figure6.3(right), the following pairs are considered.

$(i, j) \in (4, 1), (1, 2), (2, 3), (5, 4), (7, 4), (6, 5), (3, 6), (8, 7), (9, 8), (6, 9)$ Other coupled terms A_{ij} are given as $A_{ij} = 0$. In addition, matrices A_{ii}, $i = 1, 2, \cdots, 9$ can be obtained as $A_{11} = A_1 - A_{14}, A_{22} = A_2 - A_{21}, A_{33} = A_3 - A_{32}, A_{44} = A_4 - A_{45} - A_47, A_{55} = A_5 - A_{56}, A_{66} = A_6 - A_{63}, A_{77} = A_7 - A_{78}, A_{88} = A_8 - A_{89}, A_{99} = A_9 - A_{96}$. Thus, the temperature model in multiple rooms can obtain as the form of Figure6.3.

6.8 Numerical Simulation

Each parameter in the plant is given by $K_i = 1$, $T_i = 10$, $L = 0.3$, $a_{ji} = 0.1$, $b_i^a = 1$, $b_i^w = -1$, $b_i^h = 1$ and $b_i^f = -1$ respectively. For continuous-valued control inputs, the input constrains are imposed as $-3 \leq u_i(k) \leq 3$ and $-1 \leq u_i^a(k) \leq 1$ respectively.

From the matrix B_i^d, the dimension of the virtual control input is 1, and the virtual control input $u_i^v(k)$ corresponds to $-u_i^w(k) + u_i^h(k) - u_i^f(k)$. For the virtual control input

$u_i^v(k)$, the input constraint is imposed as $-3 \leq u_i(k) \leq 2$. The obtained $u_i^v(k)$ is rounded and the rounded $u_i^v(k)$, which is denoted by $u_i^r(k)$ is applied to the system. The discrete-valued control input at time t is determined by using the following look-up table:

- $u_i^r(k) = -3 : u_i^w(k) = 1, u_i^h(k) = 0, u_i^f(k) = 2,$
- $u_i^r(k) = -2 : u_i^w(k) = 1, u_i^h(k) = 0, u_i^f(k) = 1,$
- $u_i^r(k) = -1 : u_i^w(k) = 1, u_i^h(k) = 0, u_i^f(k) = 0,$
- $u_i^r(k) = 0 : u_i^w(k) = 0, u_i^h(k) = 0, u_i^f(k) = 0,$
- $u_i^r(k) = 1 : u_i^w(k) = 0, u_i^h(k) = 1, u_i^f(k) = 0,$
- $u_i^r(k) = 2 : u_i^w(k) = 0, u_i^h(k) = 2, u_i^f(k) = 0.$

Remark that the above table is not uniquely determined. In the cost function of (6.11), the weighting matrices Q, R, Q_f and the prediction horizon N are given as Q=block-diag$(Q_s, Q_s, \ldots, Q_s)$, Q_s=diag(10,0), R=block-diag$(R_s, R_s, \ldots, R_s)$, $R_s = I_5$, $Q_f = Q$, $N = 3$, respectively. Furthermore, the initial states $q_i(0), i = 1, 2, \ldots, 9$ are given as $q_1(0) = 10, q_2(0) = 12, q_3(0) = 14, q_4(0) = 16, q_5(0) = 34, q_6(0) = 35, q_7(0) = 36, q_8(0) = 32, q_9(0) = 32$ respectively, and $v_i(0) = 0$. For all rooms, the desired temperature is given as 25. For simplicity, the terminal constraint is not imposed for the system.

Next, the computation results are showed. The simulation is categorized in three cases. *Case 1* (the conventional method; MIQP problem): solving the Problem 1. *Case 2* (the existing method in [76]; QP problem): solving the Problem 2 under $u_d = 0$. It means that Problem 2 is solved with QP problem without considering the quantization error. *Case 3* (the proposed method): solving *Problem 2* under the condition that the large-scale system $\sum$ satisfies *Assumption 1.* In other words, Problem 2 is solved with QP problem with considering the effect of quantization error. By solving mixed integer linear programming (MILP) problem off-line, the control input u_d' that satisfy the desired state $x(k) = x_d$ and $x(k+1) = x_d$ is calculated.
$u_d' = \begin{bmatrix} (u_d^1)^T & (u_d^2)^T & \ldots & (u_d^9)^T \end{bmatrix}^T$, $u_d^1 = \begin{bmatrix} 0.0217 & 0.7396 & 0 \end{bmatrix}^T$,
$u_d^2 = u_d^3 = u_d^7 = u_d^8 = \begin{bmatrix} 0.0217 & 0.7381 & 0 \end{bmatrix}^T$, $u_d^4 = \begin{bmatrix} 0.0215 & 0.7320 & 0 \end{bmatrix}^T$,
$u_d^5 = \begin{bmatrix} 0.0217 & 0.7384 & 0 \end{bmatrix}^T$,
$u_d^6 = \begin{bmatrix} 0.0217 & 0.7391 & 0 \end{bmatrix}^T$ and$u_d^9 = \begin{bmatrix} 0.0216 & 0.7374 & 0 \end{bmatrix}^T$.

Figures 6.4 to 6.7 show the simulation results in *Case 1.* From Figure 6.4, it can see that the temperature converges to the desired temperature. Next, Figures 6.8 to 6.11 show the simulation results in *Case 2.* Form Figure 6.8 and 6.10, it can see the quantization errors. In other words, the auxiliary continuous-valued input does not work to compensate quantization errors. Finally, Figures 6.12 to 6.15 show the simulation results in *Case 3.* In Figure 6.12, quantization errors do not occur. The temperature trajectory in *Case 3* is similar to that in *Case 1.* Comparing Figure 6.5 with Figure 6.13, $u_i(k)$ is almost the same. Other inputs are different, because the optimal solution may not be unique.

In order to quantitatively evaluate the performance, the following performance index: $\tilde{J} = \sum_{k=0}^{9}\{\hat{x}^T(k)Q\hat{x}(k)+u^T(k)Ru(k)\}+\hat{x}^T(10)Q_f\hat{x}(10)$ is considered, where the weighting matrices are the same as those in the above simulations. Then, $\tilde{J}$=16521 for *Case 1*, $\tilde{J}$=16603 for *Case 2*, and $\tilde{J}$ =16525 for *Case 3* are obtained. From these values, it can be seen that the performance of *Case 3* is almost the same as that of *Case 1* (i.e., the optimal case). Thus, the effectiveness of introducing u_d' is clear.

Finally, the computation time for solving Problem 1 and Problem 2 is explained. In this example, IBM ILOG CPLEX Optimizer 11.0 is used as an MIQP/QP solver on the computer with the Intel Core 2 Duo 3.0 GHz processor and the 4GB memory, and for each case, the MIQP/QP problem is solved 10 times.

In *Case 1*, the worst computation time and the mean computation time of Problem 1 (the MIQP problem) were 236[sec] and 107[sec]. In Case 2, the worst computation time and the mean computation time of Problem 2 (the QP problem without considering quantization errors) were 0.0146[sec] and 0.0106[sec]. In *Case 3*, the worst computation time and the mean computation time of Problem 2 (the QP problem with considering quantization errors) were 0.0187[sec] and 0.0130[sec]. Then, it can seen that in *Case 2* and *Case 3*, Problem 2 can be solved fast. Furthermore, the performance in *Case 3* is almost the same as that in *Case 1.* Thus, the effectiveness of the proposed method (*Case 3*) is clear from the viewpoint of both the performance and the computation time.

6.9 Summary

In this chapter, based on the results of [76], a hierarchical implementation method for model predictive control of large-scale systems with both continuous-valued and discrete-

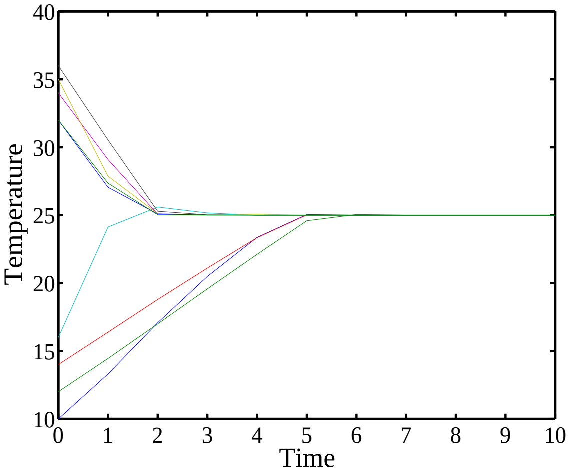


Figure 6.4: Temperature in Case 1.

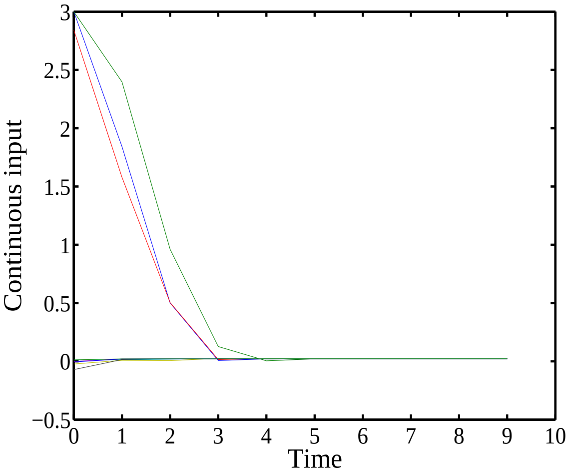


Figure 6.5: Continuous input u_i in Case 1.

valued control inputs are considered, and three topics are discussed; (i) quantization errors, (ii) stabilization via MPC, and (iii) an application to air-conditioning systems. The proposed method provides us a useful method for solving the control problem of large-scale systems. One of the future works will be to extend the proposed method to hybrid systems such as picewise affine systems. In addition, it is also important to apply the proposed method to several applications.

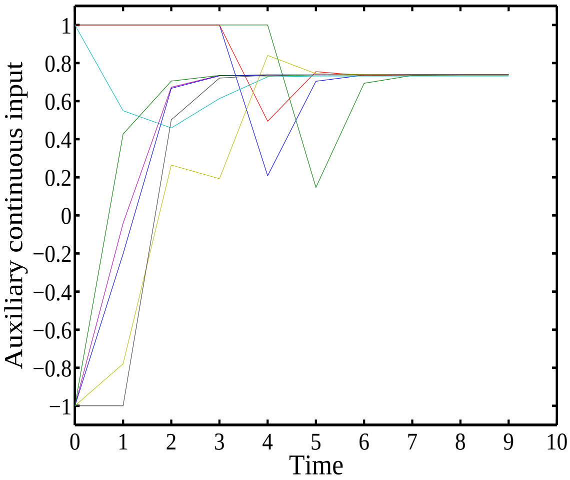


Figure 6.6: Auxiliary continuous input u_i^a in Case 1.

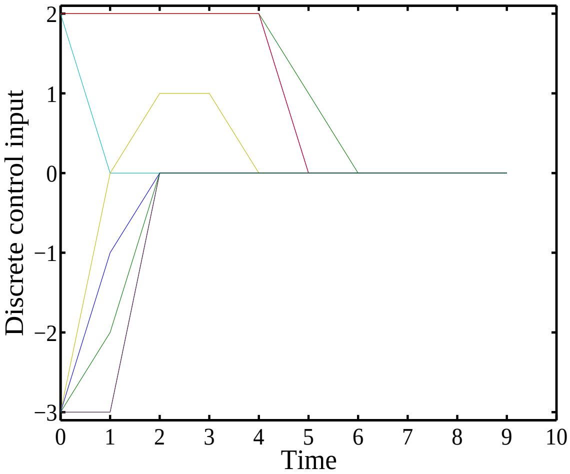


Figure 6.7: Discrete input $-u_i^w + u_i^h - u_i^f$ in Case 1.

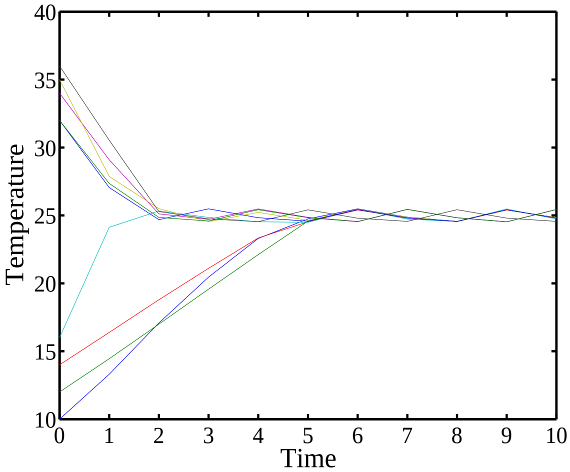


Figure 6.8: Temperature in Case 2.

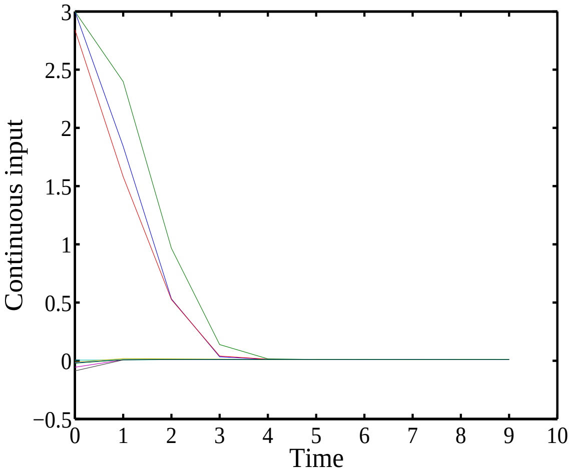


Figure 6.9: Continuous input u_i in Case 2.

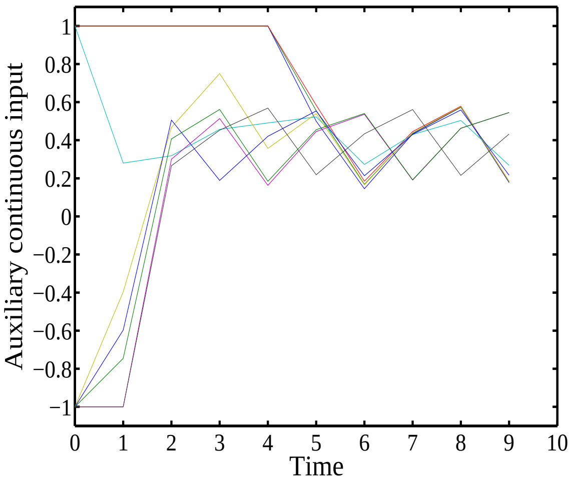


Figure 6.10: Auxiliary continuous input u_i^a in Case 2.

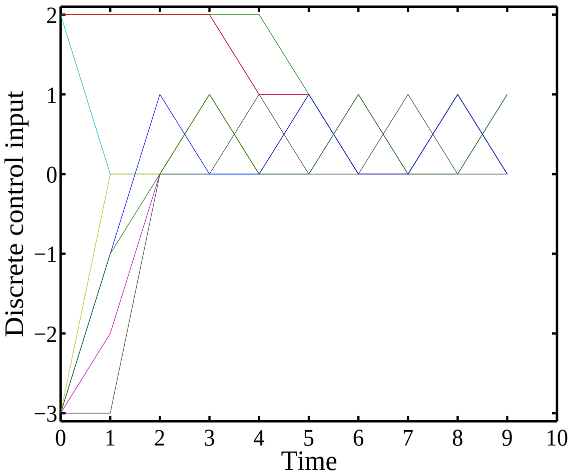


Figure 6.11: Discrete input $-u_i^w + u_i^h - u_i^f$ in Case 2.

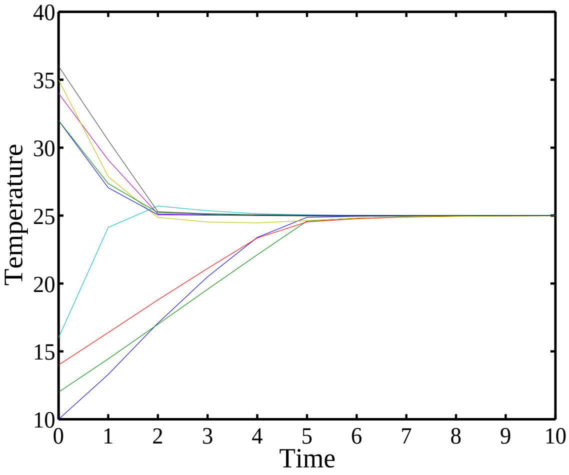


Figure 6.12: Temperature in Case 3.

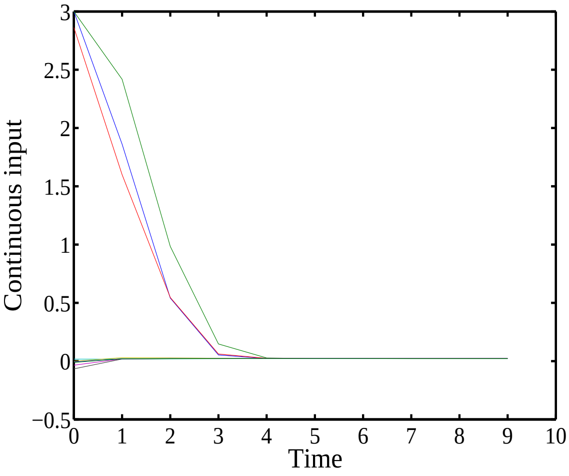


Figure 6.13: Continuous input u_i in Case 3.

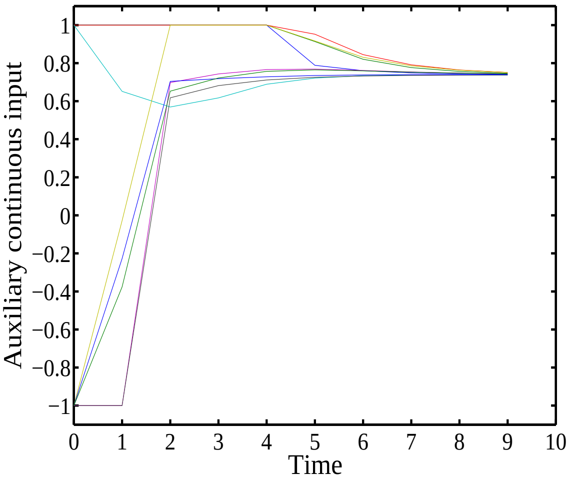


Figure 6.14: Auxiliary continuous input u_i^a in Case 3.

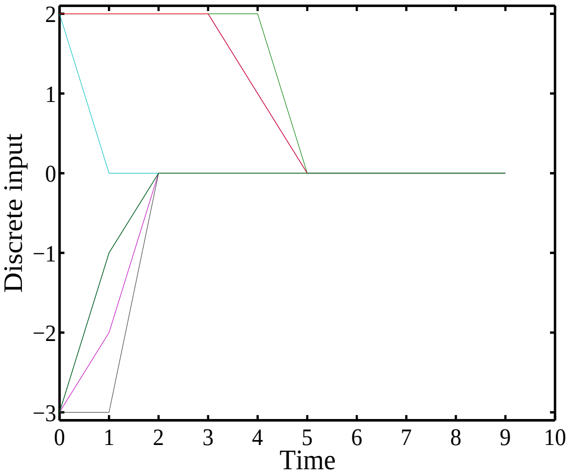


Figure 6.15: Discrete input $-u_i^w + u_i^h - u_i^f$ in Case 3.

Chapter 7

Conclusion and Future Research

7.1 Introduction

This dissertation deals with the research of technological issues for designing, implementation, analyzing and optimization algorithm of one of the application domains of cyber-physical systems (CPSs), called energy-aware smart home. Since today people are seeking smarter and better buildings that make it easier for the habitants to manage the buildings more efficiently, reducing cost and providing a better indoor environment. For this reason, hybrid temperature control with supervisory control using CPS approach in smart home environment is designed, implemented and tested.

This thesis illustrates how the energy saving heating and cooling devices can cooperate together to achieve the desired temperature without harming the user's thermal satisfaction. In this aspect the study of the effect of low cost temperature control devices such as window for natural ventilation, curtain for preventing heat gain and heat loss through the window glass and ceiling fan for air circulation are done. Upon this study, the supervisory control scheme is presented that was designed based on a thorough investigation of the environment factors such as outside temperature, solar gain and wind speed those can be used as thermal resources for controlling the room temperature.

Design and modelling of hybrid temperature control (HTC) system in smart home which is based on CPS approach to timely control the multiple actuators to maintain the desired temperature with optimized cost is presented. The advantage of my proposed HTC system over a common home temperature control system is that the system is designed

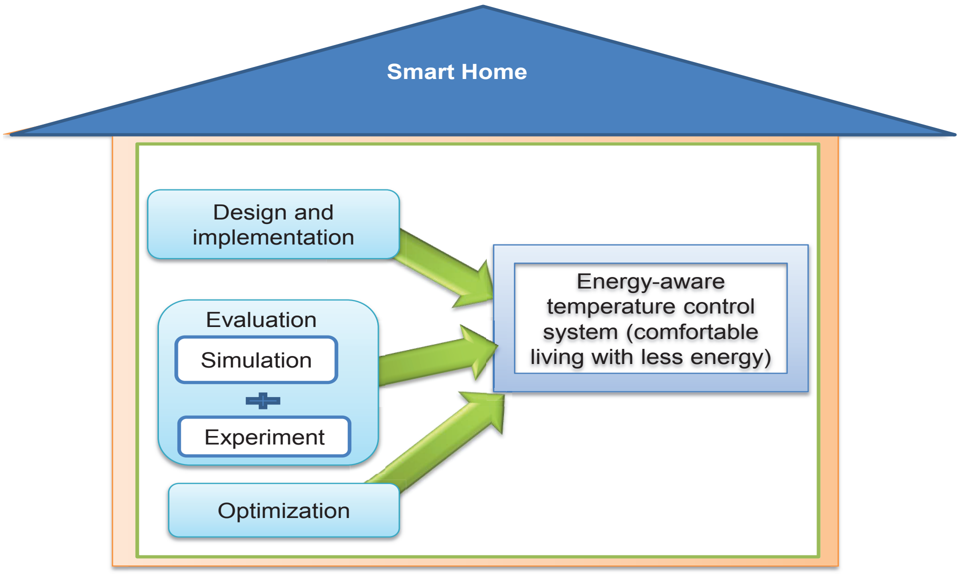


Figure 7.1: Overall of dissertation.

with interoperability among the three actuators along with the compromise between the user's preference and the energy cost. In order to show the validation of HTC system, both simulation with MATLAB/Simulink tools and experiments in iHouse are conducted. Moreover, I also consider the control problem of large-scale system which is one of the fundamental problems in control theory. From the consideration of theoretical aspects, a hierarchical implementation for model predictive control of large-scale air-conditioning system with continuous-valued and discrete-valued inputs is presented. The effectiveness of the system is that the computation load for solving the control problem of large-scale system is reduced. Figure 7.1 shows the overall of this dissertation. The temperature control system developed in this thesis contributes one of the application domains of CPS in smart home environment to approach the zero energy houses. In particular, the research objectives are proposed in the following:

1. Developing the novel application of CPS in smart home environment, which resolves the usage of electricity problem for heating and cooling in home by allowing the users to

    - improve the thermal comfort of the habitants;
    - reduce the monthly payment of electricity bills;
    - live in better and smarter life-style and this leads to the increasing the quality

of life.

2. Applying PSO algorithm to ensure the mode transition with optimized values for multi-mode hybrid automaton by minimizing the cost function.
3. To solve the computation load for MPC of multiple rooms temperature control system.

This proposed research can help the development of CPS application in smart home environment and give better solution for inhabitants who are seeking the thermal satisfaction with low cost. The following specific contributions are made to advancing the state of the art in this area.

- We present the design and implementation of CPS approach hybrid temperature control system with multiple actuators in smart home environment and study the effect of low cost temperature control devices such as window, curtain and fan in room temperature control. Through simulation we show that the amount of energy is reduced by operating those devices.
- We show the validation of the model with simulation and experiment results. We also identify the constraints in implementing the supervisory controller by analyzing the values of environment data.
- We present the simulator-based parameter optimization for state transition of multi-mode hybrid automaton using the PSO algorithm. From our proposed method, we could find the optimized values for the parameters defined for state transition (guards) by minimizing the energy cost and satisfy the constraint on user comfort level. Simulation results show that the temperature control with PSO algorithm gives better performance in the energy consumption and number of state transition times than the conventional controls.
- We present a hierarchical implementation for model predictive control of large-scale systems with continuous-valued and discrete-valued inputs for air-conditioner system. The effectiveness of the system is that we could reduce the computation load for solving the control problem of large-scale system.

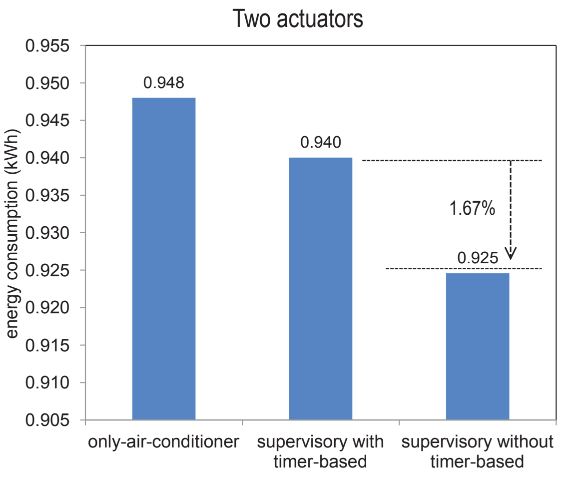


Figure 7.2: Energy consumption with two actuators.

From this contribution, we achieved three apparent solutions. Firstly, we developed a practical CPS-based smart home temperature control system. Secondly, our designed system could reduce the energy consumption of heating and cooling devices in rooms's temperature control. In Figure 7.3 and 7.3, we show the energy improvement by CPS-based HTC system with two actuators and three actuators. We can see that energy consumption for room temperature control with three actuators (air-conditioner, window, curtain) is improved by 13.4% in compare with two actuators (air-conditioner, window). Lastly, our proposed algorithm for solving control problem of large-scale system could reduce the computation load. With the proposed method, the computation time is reduced to 99.99% in compare with the existing method, MIQP (Mixed Integer Quadratic Programming) problem.

7.2 Future Work

This section discusses the future research directions for temperature control in smart home environments. With the best of my knowledge, this research contributes in the issues of a system design and implementation effort for CPS-based home temperature control system, the experiments for the system validation and optimal control problem for large scale system. However, there have still many things to improve

- considering not only the multiple actuators but also multiple resources

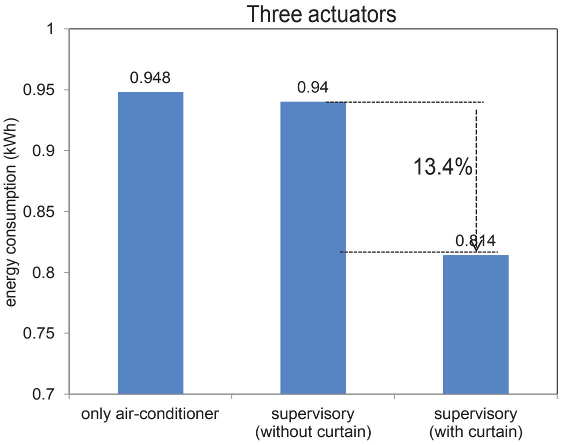


Figure 7.3: Energy consumption with three actuators.

- the problem of feedback inaccurate and incomplete information about the system's state to fulfill its speciation
- the stability of the system for such kind of multiple discrete-valued inputs and continuous-valued inputs system even the timer is defined for state transition to prevent the chattering problem
- not only the parameter optimization but also mode transition optimizing to get better performance of the system

Considering the present research, the further research will be address not only the energy efficient temperature control devices but also the multiple energy resources such as solar plant, storage battery to maintain the temperature control of whole house. Since the system will be more complex, the stability, computation and optimization problems of the system will become the critical problems need to solve out. By solving these problems, I will consider the temperature control for large scale system such as multiple rooms for large buildings, multiple houses for a city.

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Appendix A

Calculation of PMV

The equations are referenced to ( ).

$$\begin{aligned} PMV = {} & [0.303 \cdot \exp(-0.036 \cdot M) + 0.028].(M - W) - 3.05 \cdot 10^{-3} \cdot [5733 - 6.99 \cdot (M - W) - p_a] \\ & - 0.42 \cdot [(M - W) - 58.15] - 1.7 \cdot 10^{-5} \cdot M \cdot (5867 - p_a) - 0.0014 \cdot M \\ & \cdot (34 - t_a) - 3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4] - f_d \cdot h_c \cdot (t_{cl} - t_a) \end{aligned} \tag{A.1}$$

$$t_{cl} = 35.7 - 0.028 \cdot (M - W) - I_{cl} \cdot \{3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4] + f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\} \tag{A.2}$$

$$h_c = \begin{cases} 2.38 \cdot |t_{cl} - t_a|^{0.25} & \text{for } 2.38 \cdot |t_{cl} - t_a|^{0.25} > 12.1 \cdot \sqrt{var} \\ 12.1 \cdot \sqrt{var} & \text{for } 2.38 \cdot |t_{cl} - t_a|^{0.25} < 12.1 \cdot \sqrt{var} \end{cases} \tag{A.3}$$

$$f_{cl} = \begin{cases} 1.00 \cdot 1.290 l_{cl} \text{ for } l_{cl} \leq 0.078 m^2 \cdot K/W \\ 1.05 \cdot 0.645 l_{cl} \text{ for } l_{cl} > 0.078 m^2 \cdot K/W \end{cases} \tag{A.4}$$

M is the metabolic rate, in watts per square metre (W/m^2)

W is the effective mechanical power, in watts per square metre (W/m^2)

I_{cl} is the clothing insulation, in square metres Kelvin per watt $(m^2 \cdot K/W)$

f_{cl} is the clothing surface are factor

t_a is the air temperature, in degrees Celsius (℃)

$\bar{t}_r$ is the mean radiant temperature, in degrees Celsius (℃)

$v_{ar}$is the relative air velocity, in metres per second (m/s)

p_a is the water vapour partial pressure, in pascals (Pa)

h_c is the convective heat transfer coefficient, in watts per square metre Kelvin $[W/(m^2 \cdot K)]$

t_{cl} is the clothing surface temperature, in degrees Celsius (℃)

Note: 1 metabolic unit = 1met = 58.2 $/m^2$; 1 clothing unit = 1 $clo = 0.155\ m^2 \cdot$ ℃$/W$

Appendix B

Source code for MIQP problem

```
2013/03/02
% air-conditioning system
% MIQP version
% ˜A‘±“ü—Í‚ð’Ç‰Á

clear all
close all

% plant

%constant parameters
L=0.3;         %sampling time
K=1;           %constant gain
T=10;          %time costant
Bc=[ 0 1 ;1 0 ];

B0=[[0;0] [0;0]];
A0=[0 0;0 0];

%define the parameters for Room 1 to 9
Room1
a14=0.1;        %aij>0
A=[exp(-L/T) K*(1-exp(-L/T));0 0];
A14=[a14 0;0 0];
A11=A-A14;
B1v=[1;0]; B11=[Bc B1v];

%Room2
a21=0.1;        %aij>0
A21=[a21 0;0 0];
A22=A-A21;
B2v=[1;0]; B22=[Bc B2v];

%Room3
a32=0.1;        %aij>0
A32=[a32 0;0 0];
A33=A-A32;
B3v=[1;0]; B33=[Bc B3v];

%Room4
a45=0.2;  a47=0.1;      %aij>0
A45=[a45 0;0 0];A47=[a47 0;0 0];
A44=A-A45-A47;
B4v=[1;0]; B44=[Bc B4v];

%Room5
a56=0.1;        %aij>0
A56=[a56 0;0 0];
A55=A-A56;
B5v=[1;0]; B55=[Bc B5v];

%Room6
a63=0.1;        %aij>0
A63=[a63 0;0 0];
```

```
A66=A-A63;
B6v=[1;0]; B66=[Bc B6v];

%Room7
a78=0.1;        %aij>0
A78=[a78 0;0 0];
A77=A-A78;
B7v=[1;0]; B77=[Bc B7v];

%Room8
a89=0.1;        %aij>0
A89=[a89 0;0 0];
A88=A-A89;
B8v=[1;0]; B88=[Bc B8v];

%Room9
a96=0.1;        %aij>0
A96=[a96 0;0 0];
A99=A-A96;
B9v=[1;0]; B99=[Bc B9v];

A=[A11 A0 A0 A14 A0 A0 A0 A0 A0;
   A21 A22 A0 A0 A0 A0 A0 A0 A0;
   A0 A32 A33 A0 A0 A0 A0 A0 A0;
   A0 A0 A0 A44 A45 A0 A47 A0 A0;
   A0 A0 A0 A0 A55 A56 A0 A0 A0;
   A0 A0 A63 A0 A0 A66 A0 A0 A0;
   A0 A0 A0 A0 A0 A0 A77 A78 A0;
   A0 A0 A0 A0 A0 A0 A0 A88 A89;
   A0 A0 A0 A0 A0 A96 A0 A0 A99];

Bc = blkdiag(Bc,Bc,Bc,Bc,Bc,Bc,Bc,Bc,Bc);

Bd = [ -3 -2 -1 1 2 ; 0 0 0 0 0 ];
Bd = blkdiag(Bd,Bd,Bd,Bd,Bd,Bd,Bd,Bd,Bd);

% xopt, vopt
n = size(A,1);
mc = size(Bc,2);
md = size(Bd,2);
m = mc+md;

% input constraints
umin = [ -3 ; -1 ];
umax = [ +3 ; +1 ];

umin = [ umin ; umin ; umin ; umin ; umin ; umin ; umin ; umin ; umin ];
umax = [ umax ; umax ; umax ; umax ; umax ; umax ; umax ; umax ; umax ];

% Cx+D1uc+D2ud<=E
C  = zeros(45,18);
D1 = [ -eye(size(umin,1)) ;
       +eye(size(umin,1)) ;
       zeros(9,18)];
D2 = [ zeros(36,45);

blkdiag(ones(1,5),ones(1,5),ones(1,5),ones(1,5),ones(1,5),ones(1,5),ones(1,
5),ones(1,5),ones(1,5)) ];
E  = [ -umin ; +umax ; ones(9,1) ];
```

```
 % initial state
x10 = [10;0];
x20 = [12;0];
x30 = [14;0];
x40 = [16;0];
x50 = [34;0];
x60 = [35;0];
x70 = [36;0];
x80 = [32;0];
x90 = [32;0];

x0 = [x10;x20;x30;x40;x50;x60;x70;x80;x90];

% desired state
xd = [[25;0];[25;0];[25;0];[25;0];[25;0];[25;0];[25;0];[25;0];[25;0]];

% desired input
ud = zeros(63,1);

% weighting matrices
Q = 10*[ 1 0 ; 0 0 ];
Q = blkdiag(Q,Q,Q,Q,Q,Q,Q,Q,Q);
Qf = Q;
R = eye(63);

f = 3; % prediction horizon
T = 10; % simulation time

x_seq = x0;
u_seq = [];

x_current = x0;

c_time_seq = [];

for i=1:T
i

% solve the optimal control problem
[ c_time, opt, xopt, vopt, status ] = ...
mld2miqp(A, Bc, [], Bd, C, D1, [], D2, E, Q, R, Qf, f, x_current, xd, ud);

u_current = vopt(1:m);
x_next = A * x_current + [ Bc Bd ] * u_current;

udis = Bd*u_current(19:63);
udis = udis([1,3,5,7,9,11,13,15,17]);
%udis = udis([2,4,6,8,10,12,14,16,18]);

x_seq = [ x_seq x_next ];
u_seq = [ u_seq [ u_current(1:18) ; udis ] ];
x_current = x_next;
c_time_seq = [ c_time_seq ; c_time ];

end

figure
plot([0:T],x_seq([1,3,5,7,9,11,13,15,17],:)')
```

```
figure
plot([0:T-1],u_seq([1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18],:)')

%figure
%plot([0:T-1],u_seq([1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18],:)')

figure
plot([0:T-1],u_seq([19,20,21,22,23,24,25,26,27],:)')
```

Source code for MIQP problem (Open in CPLEX)

```
function [ c_time, opt, xopt, vopt, status ] = ...
mld2miqp(A, B1, B2, B3, C, D1, D2, D3, F, Q, R, Qf, f, x0, xd, ud)

n = size(A,2);
m1 = size(B1,2);
m2 = size(B2,2);
m3 = size(B3,2);

% x(k+1) = A x(k) + B1 u(k) + B2 z(k) + B3 delta(k)
% C x(k) + D1 u(k) + D2 z(k) + D3 delta(k) <= F
% Ceq x(k) + Deq1 u(k) + Deq2 z(k) + Deq3 delta(k) = Feq
% ->
% x(k+1) = A x(k) + B v(k)
% C x(k) + D v(k) <= F
% Ceq x(k) + Deq v(k) = Feq
%

B = [ B1 B2 B3 ];
D = [ D1 D2 D3 ];

%%%%% MLD -> MIQP %%%%%

% Abar, xdbar, udbar
Abar = eye(n);
xdbar = xd;
udbar = [];

for i = 1 : f
    Abar = [ Abar ; A^i ];
    xdbar = [ xdbar ; xd ];
    udbar = [ udbar ; ud ];
end

% Bbar = Bbar_pre1 * Bbar_pre2
Bbar_pre1 = zeros( (f+1)*n, f*n );

for i = 1 : +1 : f
    Bbar_pre1(:,(i-1)*n+1:i*n) = [ zeros(n*i,n) ; Abar(1:(f-i+1)*n,:) ];
end

Bbar_pre2 = [];

for i = 1 : f
    Bbar_pre2 = blkdiag(Bbar_pre2, B);
```

```
end

Bbar = Bbar_pre1 * Bbar_pre2;

% Qbar
Qbar = Q;

for i = 1 : f-1
    Qbar = blkdiag(Qbar, Q);
end

Qbar = blkdiag(Qbar, Qf);


% Rbar
Rbar = R;

for i = 1 : f-1
    Rbar = blkdiag(Rbar, R);
end


% Cbar, Dbar, Fbar
Cbar = C;
Dbar = D;
Fbar = F;

for i = 1 : f-1
    Cbar = blkdiag(Cbar, C);
    Dbar = blkdiag(Dbar, D);
    Fbar = [ Fbar ; F ];
end

% ’?ˆÓ
% Cbar = blkdiag(Cbar, C);
% Dbar = [ Dbar ; zeros(size(D,1),size(Dbar,2)) ];
% Fbar = [ Fbar ; F ];

Cbar = [ Cbar zeros(size(Cbar,1),size(C,2)) ];   % ’?ˆÓ


% MIQP
%
% min  v^T M1 v + M2' v
% s.t. L1   v <= L2
%      L1eq v  = L2eq

% M1 = 2 * ( Bbar' * Qbar * Bbar + Rbar );
% M1 = ( M1 + M1' ) / 2;
% M2 = 2 * Bbar' * Qbar * Abar * x0;

M1 = 2 * ( Bbar' * Qbar * Bbar + Rbar );
M1 = ( M1 + M1' ) / 2;
M2 = 2*Bbar'*Qbar*Abar*x0 - 2*Bbar'*Qbar*xdbar - 2*Rbar*udbar;

L1 =  Cbar * Bbar + Dbar;
L2 = -Cbar * Abar * x0 + Fbar;
```

```
%L1eq =  Ceqbar * Bbar + Deqbar;
%L2eq = -Ceqbar * Abar * x0 + Feqbar;


% 0-1•Ï?”,Æ,È,é—v‘f,ðŽw’è

ivar = zeros( 1, f*m3 );

for i = 1 : f
    for j = 1 : +1 : m3
        ivar( 1, m3*(i-1)+j ) = (m1+m2+m3)*(i-1) + (m1+m2) + j;
    end
end

nL1 = size(L1,1);
%nL1eq = size(L1eq,1);

%%%%% CPLEX,Å‰ð,- %%%%%
D      = [];
Z      = [];
X      = [];
Time   = [];
%
PTYPE                        = 1;
CTYPE                        = [];
CTYPE( 1 : nL1 )             = 'L';
%CTYPE( nL1+1 : nL1+nL1eq )   = 'E';
CTYPE                        = char(CTYPE)';
LB                           = [];
UB                           = [];
RANGEVAR                     = [];
VARTYPE                      = [];
VARTYPE( 1 : (m1+m2+m3)*f )  = 'C';
%VARTYPE( 1 : (nu+nd+nz)*T )  = 'C';
VARTYPE( ivar )           = 'B';
%VARTYPE( vartype )           = 'B';
%VARTYPE( zdvartype )         = 'B';
VARTYPE                      = char(VARTYPE)';
X0I                          = [];
X0                           = [];
VERBOSE                      = 0;
SAVE                         = 1;
%
%for j = 0:0
tic;

[vopt,opt,status,extra] = ...
      cplexmex( PTYPE, M1, M2, L1, L2, CTYPE, LB, UB, ...
                  VARTYPE, X0, [], SAVE );

%Tend = toc
%'--------------------------------------------------'
 toc;
c_time = toc;

opt

status
 xopt = Abar * x0 + Bbar * vopt;
```

Appendix C

Source code for QP problem

```
clear all
close all

% plant

L=0.3;          %sampling time
K=1;            %constant gain
T=10;           %time constant

Bc=[ 0 1 ;1 0];
B0=[[0;0] [0;0] [0;0]];
A0=[0 0;0 0];

%define the parameters for Room 1 to 9
%Room1
a14=0.1;         %aij>0
A=[exp(-L/T) K*(1-exp(-L/T));0 0];
A14=[a14 0;0 0];
A11=A-A14;
B1v=[1;0]; B11=[Bc B1v];

%Room2
a21=0.1;         %aij>0
A21=[a21 0;0 0];
A22=A-A21;
B2v=[1;0]; B22=[Bc B2v];

%Room3
a32=0.1;         %aij>0
A32=[a32 0;0 0];
A33=A-A32;
B3v=[1;0]; B33=[Bc B3v];

%Room4
a45=0.2;  a47=0.1;      %aij>0
A45=[a45 0;0 0];A47=[a47 0;0 0];
A44=A-A45-A47;
B4v=[1;0]; B44=[Bc B4v];

%Room5
a56=0.1;         %aij>0
A56=[a56 0;0 0];
A55=A-A56;
B5v=[1;0]; B55=[Bc B5v];

%Room6
a63=0.1;         %aij>0
A63=[a63 0;0 0];
A66=A-A63;
B6v=[1;0]; B66=[Bc B6v];

%Room7
a78=0.1;         %aij>0
A78=[a78 0;0 0];
A77=A-A78;
```

```
B7v=[1;0]; B77=[Bc B7v];

%Room8
a89=0.1;        %aij>0
A89=[a89 0;0 0];
A88=A-A89;
B8v=[1;0]; B88=[Bc B8v];

%Room9
a96=0.1;        %aij>0
A96=[a96 0;0 0];
A99=A-A96;
B9v=[1;0]; B99=[Bc B9v];

A=[A11 A0 A0 A14 A0 A0 A0 A0 A0;
   A21 A22 A0 A0 A0 A0 A0 A0 A0;
   A0 A32 A33 A0 A0 A0 A0 A0 A0;
   A0 A0 A0 A44 A45 A0 A47 A0 A0;
   A0 A0 A0 A0 A55 A56 A0 A0 A0;
   A0 A0 A63 A0 A0 A66 A0 A0 A0;
   A0 A0 A0 A0 A0 A0 A77 A78 A0;
   A0 A0 A0 A0 A0 A0 A0 A88 A89;
   A0 A0 A0 A0 A0 A96 A0 A0 A99];

B=[B11 B0 B0 B0 B0 B0 B0 B0 B0;
   B0 B22 B0 B0 B0 B0 B0 B0 B0;
   B0 B0 B33 B0 B0 B0 B0 B0 B0;
   B0 B0 B0 B44 B0 B0 B0 B0 B0;
   B0 B0 B0 B0 B55 B0 B0 B0 B0;
   B0 B0 B0 B0 B0 B66 B0 B0 B0;
   B0 B0 B0 B0 B0 B0 B77 B0 B0;
   B0 B0 B0 B0 B0 B0 B0 B88 B0;
   B0 B0 B0 B0 B0 B0 B0 B0 B99];

% xopt, vopt
n = size(A,1);
m = size(B,2);

% input constraints
umin = [ -3 ; -1 ; -3 ];
umax = [ +3 ; +1 ; +2 ];

umin = [ umin ; umin ; umin ; umin ; umin ; umin ; umin ; umin ; umin ];
umax = [ umax ; umax ; umax ; umax ; umax ; umax ; umax ; umax ; umax ];

% Cx+Du<=E
C = zeros(2*size(umin,1),18);
D = [ -eye(size(umin,1)) ; +eye(size(umin,1)) ];
E = [ -umin ; +umax ];

% initial state

x10 = [10;0];x20 = [12;0];x30 = [14;0];x40 = [16;0];x50 = [34;0];
x60 = [35;0];x70 = [36;0];x80 = [32;0];x90 = [32;0];

x0 = [x10;x20;x30;x40;x50;x60;x70;x80;x90];

% desired state
xd = [[25;0];[25;0];[25;0];[25;0];[25;0];[25;0];[25;0];[25;0];[25;0]];
```

```
% desired input
ud1 = [ 0.0217 0.7396 0 ]';
ud2 = [ 0.0217 0.7381 0 ]';
ud3 = [ 0.0217 0.7381 0 ]';
ud4 = [ 0.0215 0.7320 0 ]';
ud5 = [ 0.0217 0.7384 0 ]';
ud6 = [ 0.0217 0.7391 0 ]';
ud7 = [ 0.0217 0.7381 0 ]';
ud8 = [ 0.0217 0.7381 0 ]';
ud9 = [ 0.0216 0.7374 0 ]';

% If ud=0, then quantization errors occur.
ud = zeros(27,1);

% If the following ud is used, then quantization errors do not occur.
ud = [ ud1 ; ud2 ; ud3 ; ud4 ; ud5 ; ud6 ; ud7 ; ud8 ; ud9 ];

% weighting matrices
Q = 10*[ 1 0 ; 0 0 ];
Q = blkdiag(Q,Q,Q,Q,Q,Q,Q,Q,Q);
Qf = Q;
R = eye(27);

% prediction horizon
f = 3;

% simulation time
T = 10;

x_seq = x0;
u_seq = [];

x_current = x0;

c_time_seq = [];

% using virtual values or descrete values.
use_uv = false;
% true: The virtual control input is directly applied to the plant.
% false: The virtual control input is transformed into the discrete valued
input.

for i=1:T
%
i

%x_current

% solve the optimal control problem
[ c_time, opt, xopt, vopt, status ] = ...
linear2qp(A, B, C, D, E, Q, R, Qf, f, x_current, xd, ud);

% calculation of the next state of the system.
if use_uv
    % Using virtual control inputs.
    u_current = vopt(1:m);
    x_next = A * x_current + B * u_current;
else
    % Using descrete control inputs.
```

```
    vc = vopt([1,2,4,5,7,8,10,11,13,14,16,17,19,20,22,23,25,26]);
    vv = vopt([3,6,9,12,15,18,21,24,27]);
    vd = round(vv);
    u_current = [ vc(1) vc(2) vd(1) vc(3) vc(4) vd(2) vc(5) vc(6) vd(3)
vc(7) vc(8) vd(4) vc(9) vc(10) vd(5) vc(11) vc(12) vd(6) vc(13) vc(14)
vd(7) vc(15) vc(16) vd(8) vc(17) vc(18) vd(9) ]';
    %u_current = [];
    %for j=1:9
    %    u_current = [ u_current ; vc(j) ; vd(j) ];
    %end
    x_next = A * x_current + B * u_current;
end

%x_next = A * x_current + B * vopt(1:m);

x_seq = [ x_seq x_next ];
u_seq = [ u_seq u_current ];
x_current = x_next;
c_time_seq = [ c_time_seq ; c_time ];

end

% x_seq = [];
%
% for i = 0 : +1 : f
%     x_seq( 1:n, i+1 ) = xopt( n*i+1 : n*i+n );    % xd
% end
%
% u_seq = [];
%
% for i = 0 : +1 : f-1
%     u_seq( 1:m, i+1 ) = vopt( m*i+1 : m*i+m );    % xd
% end

figure
plot([0:T],x_seq([1,3,5,7,9,11,13,15,17],:)')

figure
plot([0:T-1],u_seq([1,4,7,10,13,16,19,22,25],:)')

figure
plot([0:T-1],u_seq([2,5,8,11,14,17,20,23,26],:)')

figure
plot([0:T-1],u_seq([3,6,9,12,15,18,21,24,27],:)')
```

Source code for QP problem (Open in CPLEX)

```
 function [ c_time, opt, xopt, vopt, status ] = ...
linear2qp(A, B, C, D, E, Q, R, Qf, f, x0, xd, ud)



n = size(A,2);
m = size(B,2);



%
```

```
% x(k+1) = A x(k) + B1 u(k) + B2 z(k) + B3 delta(k)
% C x(k) + D1 u(k) + D2 z(k) + D3 delta(k) <= F
% Ceq x(k) + Deq1 u(k) + Deq2 z(k) + Deq3 delta(k) = Feq
% ->
% x(k+1) = A x(k) + B v(k)
% C x(k) + D v(k) <= F
% Ceq x(k) + Deq v(k) = Feq
%

%B = [ B1 B2 B3 ];
%D = [ D1 D2 D3 ];
%Deq = [ Deq1 Deq2 Deq3 ];


%%%%% MLD -> MIQP %%%%%

% Abar, xdbar, udbar
Abar = eye(n);
xdbar = xd;
udbar = [];

for i = 1 : f
    Abar = [ Abar ; A^i ];
    xdbar = [ xdbar ; xd ];
    udbar = [ udbar ; ud ];
end


% Bbar = Bbar_pre1 * Bbar_pre2
Bbar_pre1 = zeros( (f+1)*n, f*n );

for i = 1 : +1 : f
    Bbar_pre1(:,(i-1)*n+1:i*n) = [ zeros(n*i,n) ; Abar(1:(f-i+1)*n,:) ];
end

Bbar_pre2 = [];

for i = 1 : f
    Bbar_pre2 = blkdiag(Bbar_pre2, B);
end

Bbar = Bbar_pre1 * Bbar_pre2;


% Qbar
Qbar = Q;

for i = 1 : f-1
    Qbar = blkdiag(Qbar, Q);
end

Qbar = blkdiag(Qbar, Qf);


% Rbar
Rbar = R;

for i = 1 : f-1
```

```
    Rbar = blkdiag(Rbar, R);
end


% Cbar, Dbar, Fbar
Cbar = C;
Dbar = D;
Ebar = E;

for i = 1 : f-1
    Cbar = blkdiag(Cbar, C);
    Dbar = blkdiag(Dbar, D);
    Ebar = [ Ebar ; E ];
end

% ’?ˆÓ
% Cbar = blkdiag(Cbar, C);
% Dbar = [ Dbar ; zeros(size(D,1),size(Dbar,2)) ];
% Fbar = [ Fbar ; F ];

Cbar = [ Cbar zeros(size(Cbar,1),size(C,2)) ];    % ’?ˆÓ


% Ceqbar, Deqbar, Feqbar
%Ceqbar = Ceq;
%Deqbar = Deq;
%Feqbar = Feq;

% for i = 1 : f-1
%     Ceqbar = blkdiag(Ceqbar, Ceq);
%     Deqbar = blkdiag(Deqbar, Deq);
%     Feqbar = [ Feqbar ; Feq ];
% end

% ’?ˆÓ
% Ceqbar = blkdiag(Ceqbar, Ceq);
% Deqbar = [ Deqbar ; zeros(size(Deq,1),size(Deqbar,2)) ];
% Feqbar = [ Feqbar ; Feq ];

%Ceqbar = [ Ceqbar zeros(size(Ceqbar,1),size(Ceq,2)) ];    % ’?ˆÓ


% MIQP
%
% min  v^T M1 v + M2' v
% s.t. L1   v <= L2
%      L1eq v  = L2eq

M1 = 2 * ( Bbar' * Qbar * Bbar + Rbar );
M1 = ( M1 + M1' ) / 2;
%M2 = 2 * Bbar' * Qbar * Abar * x0;
M2 = 2*Bbar'*Qbar*Abar*x0 - 2*Bbar'*Qbar*xdbar - 2*Rbar*udbar;

L1 =  Cbar * Bbar + Dbar;
L2 = -Cbar * Abar * x0 + Ebar;

%L1eq =  Ceqbar * Bbar + Deqbar;
%L2eq = -Ceqbar * Abar * x0 + Feqbar;
```

```
% 0-1•Ï?”,Æ,È,é—v‘f,ðŽw’è

% ivar = zeros( 1, f*m3 );
%
% for i = 1 : f
%     for j = 1 : +1 : m3
%         ivar( 1, m3*(i-1)+j ) = (m1+m2+m3)*(i-1) + (m1+m2) + j;
%     end
% end


nL1 = size(L1,1);
%nL1eq = size(L1eq,1);


%%%%% CPLEX,Å‰ð,- %%%%%
D     = [];
Z     = [];
X     = [];
Time  = [];
%
PTYPE                        = 1;
CTYPE                        = [];
CTYPE( 1 : nL1 )             = 'L';
%CTYPE( nL1+1 : nL1+nL1eq )   = 'E';
CTYPE                        = char(CTYPE)';
LB                           = [];
UB                           = [];
RANGEVAR                     = [];
VARTYPE                      = [];
VARTYPE( 1 : m*f )           = 'C';
%VARTYPE( 1 : (nu+nd+nz)*T )  = 'C';
%VARTYPE( ivar )           = 'B';
%VARTYPE( vartype )           = 'B';
%VARTYPE( zdvartype )         = 'B';
VARTYPE                      = char(VARTYPE)';
X0I                          = [];
X0                           = [];
VERBOSE                      = 0;
SAVE                         = 1;
%
%for j = 0:0
tic;

[vopt,opt,status,extra] = ...
      cplexmex( PTYPE, M1, M2, L1, L2, CTYPE, LB, UB, ...
                  VARTYPE, X0, [], SAVE );

%Tend = toc
%'--------------------------------------------------'

toc;
c_time = toc;

opt

status
```

```
xopt = Abar * x0 + Bbar * vopt;
```