Development of Home Simulation with Thermal Environment and Electricity Consumption

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Abstract

Energy management systems have been developed in order to achieve goal of energy efficiency in the focused areas. Home simulation is one of the tools that can simulate electricity consumption based on the home appliances usage. However, several elements were ignored in traditional home simulation. In this paper, we introduce the home simulation, which can simulate not only the electric power and its consumption, but also the thermal energy consumption. Relationships among five elements are considered in the home simulation. To validate the performance of the proposed home simulation, a real experimental house is used to conduct the experiment. The results showed the ability of the proposed home simulation to simulate the thermal energy and estimate the temperature of various rooms with an error of 1.2 degrees Celsius. Furthermore, the electricity consumption is also simulated based on the human activity schedule and home appliances usage.

Keywords: Energy management system, Home simulation, Electric power consumption, Thermal energy

1 Introduction

Recently, the use of energy has multiplied more rapidly than ever before, and is projected to grow even more rapidly year by year. Energy Management System (EMS) is one of the systems that most researchers aim to develop in order to reduce peaks in power usage, ensure effective and efficient use of energy, and reduce energy wastage in the building. Nowadays, energy consumption in building, including home, is a large share of the world's total end use of energy [1]. The electric demand is increasing gradually time by time, whereas the present infrastructure has a limitation of capability to produce the electricity. Therefore, balancing the electric supply and demand in the building is a challenging task, especially in home building.

Currently, the energy efficiency in home can be achieved by integrating smart devices into home environment. Numerous intelligent sensor networks are installed inside and outside home environment. The context-aware information such as temperature, humidity, home appliance usage can be obtained, which is used for controlling the operation of home appliance. For example, if the outside temperature is more comfortable than inside temperature, the home system will control the opening or closing window instead turning on/off air-conditioner [2]. As the result, the amount of consumed energy will be reduced. Nonetheless, considering only the home appliance usage is not enough in some circumstances. Thermal energy is one of the factors that affects to the overall electricity consumption. As for the electricity consumption in the home, over 50% of overall electricity consumption is consumed by heating/cooling devices [1]. Consequently, the thermal energy and the electric power consumption should be investigated in the home simulation.

With the development of the home simulation, it is more complex than the traditional home simulation. Several elements were not considered in the previous research works. To address this

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shortcoming, we propose an experimental home simulation, which can simulate not only the electricity consumption, but also the thermal energy. The relationships among five elements: house, home appliance, physical environment, electric power, and human are investigated in this research. Moreover, parameter estimation technique is adopted in thermal model in order to estimate uncertain parameters such as coefficient of heat capacity, coefficient of solar radiation, or coefficient of device heat. To validate the proposed simulation, we implement and verify the proposed simulation based on the real house, called iHouse [3]. Thus, the reliable results can be observed in this simulation.

2 Related Works

Smart community energy management system has emerged as one of the mainstream approaches to support the electricity delivery system in the city. Toshiba has launched the pilot project in Yokohama prefecture, called Yokohama Smart City Project (YSCP) [4]. They aim to build the system that uses energy effectively on a community-wide scale. Fujitsu presented the practical plan to create cities that can balance between environmental considerations and ease of living by introducing EMS solutions [5]. There are a number of different types of EMS, which have been presented in several research works. Building Energy Management System (BEMS) was proposed in Smitha's research [6]. They aim to reduce the energy consumption in commercial building and to ensure customers' comfort. Fuzzy logic controllers were used to control the lighting and air conditioning systems by proper selection of illumination and temperature according to the customers' preferences.

Home Energy Management System (HEMS) is an essential system to realize the energy consumption management in the home. The development of technologies like wireless sensor network (WSN), data communication, and security play a significant role to produce ambient intelligence in the home. Home environment information can be obtained through the home network. ECHONET [7] was presented as an international home network protocol standard used to control, monitor, and gather information from the home appliances and the sensors. W. Torresani et al. [8] proposed the WSN for monitoring the physical quantities affecting indoor thermal comfort. Four sensors–temperature sensor, humidity sensor, radiation sensor, and air-flow sensor, were used to collect the environment data in the room.

Home simulations now have been proposed in order to simulate and validate the energy usage. P. Kordik et al. [9] presented the building automation simulator for intelligent and energy efficient home. Inductive neural networks were developed in the Amigo framework in order to evolve most efficient control strategy. Lights in each room were controlled based on the selected strategy. However, the current home simulation still have limitation. A few factors have been considered in the home simulations. N. Gudi et al. [10] aimed to optimize the energy consumption based on only the home appliance usage. C. A. Carmody et al. [11] have attempted to identify thermal parameters for houses but their models do not take into account a number of parameters about external environment such as solar radiation or wind velocity. Therefore, this paper aims to propose the complex home simulation, which can simulate both the electricity consumption and the thermal energy.

3 Home Simulation Architecture

A layered architecture of home simulation is designed for interoperation among five simulators. It consists of four layers as shown in Fig. 1. Individual simulation layer is proposed as a core program of each simulator. In our proposed home simulation, physical environment simulator is implemented based on MATLAB/Simulink environment, which supports user-friendly interface and the ability of analyzing simulation results, while the rest four simulators are developed under Python environment. Nonetheless, each simulator cannot communicate to each other because the environment of each simulator is different. Adapter layer is implemented for help two incompatible environment to work together. Moreover, the adapter layer has the responsibility to organize the message from other layers.

To communicate with each other, we create a shared library, called SimHome library, in communication layer. The SimHome library acts as a network interface in the home simulation. In this sense, adapter software in each simulator can interact with simulation manager layer via SimHome library. The simulation manager layer has a significant role to manage the data, and to synchronize the time in the proposed home sim-

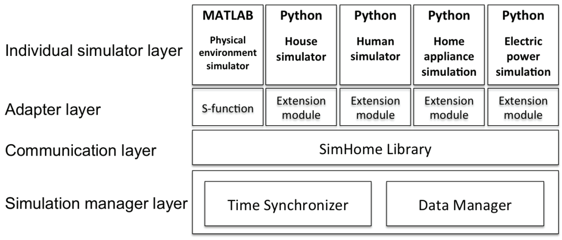

Figure 1: The examples of layered architecture of physical environment simulator

ulation. Time synchronizer module is proposed to receive a register of each simulator, and make it work together, while data manager module has a duty to send and receive massage among the five simulators.

4 Home Simulation Model

In modelling of a resident home, five elements have been investigated: house, home appliance, physical environment, electric power, and human. These five elements have an relationships as shown in Fig. 2.

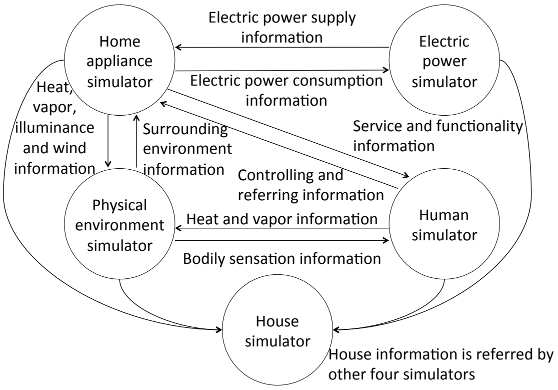

Figure 2: Relationships among the five elements

- **House Simulator**

  House simulator interacts with other simulators as a center of home simulation. House information can be referred from the blueprint of the house. For example, the thermal model should get the information about the material of wall of each room in order to calculate the heat transfer between rooms. Meanwhile, the human location or object location can be retrieved from the layout of the home.

- **Human Simulator**

  Human Simulator plays a significant role to interact with home appliance and physical environment simulators. Human activity schedule is simulated based on NHK survey [12]. NHK broadcasting culture research institute has collected the survey regarding the use of time in the daily lives of Japanese citizens in 2005. The generated human activity schedule links to home appliance simulator. Thus, home appliances will be controlled depending on the state dynamically. In addition, heat emission from the human body is considered as one of physical environment in the room.

- **Physical Environment Simulator**

  Physical Environment Simulator [13] mainly focuses on the thermal energy in each room. Figure 3 shows the structure of physical environment simulator. The house model is retrieved from the house simulator. Thermal model then calculates the change of room temperature by calculating heat fluxes coming and escaping a room using equation as shown in Eq 1.

$$\frac{\partial T}{\partial t} = \frac{1}{C_v} \sum_i Q_i(t) \qquad (1)$$

where $Q_i(t)$ are heat fluxes going out or coming in the room at time t. C_v is the heat capacity of the room. Furthermore, Simulink Design Optimization toolbox [14] is used to identify uncertain parameters. The toolbox runs the thermal model a number of times and adjusts parameters based on an optimization algorithm such as trust region reflective algorithm.

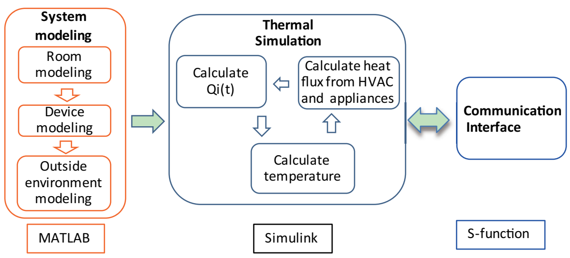

Figure 3: Structure of physical environment simulator

- **Home Appliance Simulator**

  Home appliances in this simulator work as ECHONET [7] devices. This means that we can know the location, network address, object model, property map, and state of the appliances. Home appliance simulator is an important element because it affects to all elements in the home simulation. For example, resident turns on air-conditioner through home service (human simulator). The home simulation receives the location, and ID of the air-conditioner (house simulation). Air-conditioner then changes the atmosphere in the room (physical environment simulator), and also consumes a lot of electricity (electric power simulator).

- **Electric Power Simulator**

  Electric consumption in this simulator is calculated based on wattage and time operation, then summarizes the overall electricity consumption. The home simulation can optimize the electricity consumption based on the home appliance usage. For example, the simulation can detect the peak load when home appliances consume the electricity over the limitation. Thus, the simulation can create an optimizing policy to shift their electricity usage during peak periods in response to time-based rate.

5 Simulation Results

5.1 Simulation Environment

The real home environment, called iHouse, is used to validate the performance of our proposed home simulation as presented in Fig 4. The design was based on the standard house model of AIJ (Architectural Institute of Japan). Two floors Japanese-style house with 10 rooms, more than 250 sensors (e.g., temperature sensors, humidity sensors, illumination sensors) and home appliances are connected to the home network.

To simulate the results, configuration files such as house model, human activity dataset, or weather information are added as an input of the home simulation. Experimental scenario is set as follows:

- **The number of residents**: One family with four members (father, mother, and two children)

Figure 4: iHouse

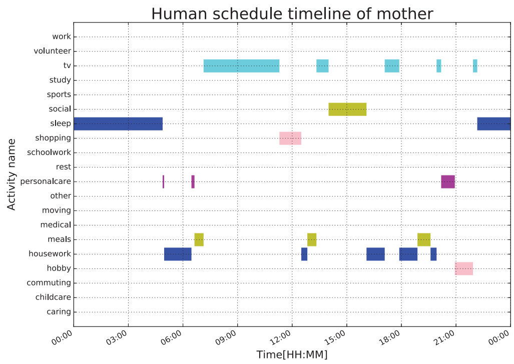

Figure 5: Human schedule timeline of mother

- **Experimental date**: August 1, 2012
- **Human activity schedule**: 20 activities are generated based on NHK survey as indicated in Fig. 5.
- **Weather information**: Environment parameters, such as outside temperature, wind direction, and sunlight direction, are retrieved from Japan Meteorological Agency.

5.2 Results

To validate the performance of home simulation, comparative experiment is conducted in this section. Eight temperature sensors are deployed in each room for measuring the room temperature. At the same time, the home simulation simulates the room temperature in iHouse based on the weather information such as outside temperature, wind direction, and sunlight direction. Parameter estimation technique is used in this simulator to calculate the heat transfer between rooms in the iHouse. Figure 6 displays results of temperature difference between measured temperature data and simulated temperature data.

The comparative experiment was investigated under condition of air-conditioner OFF. As results, the temperature differences between measured room temperature and simulated temperature are maximum 1.2 degree Celsius.

After the proposed home simulation was validated, we examined another experiment, which considers all of elements as described in Section 4. Figure 7 demonstrates the simulated temperature results in six rooms. Living room is an example of changing room temperature when the resident is performing the activity. The home simulation will simulate the ON status of air-conditioner when the resident in the room feels uncomfortable. This is calculated based on temperature and humidity in the room. From the results, not only the room temperature in the living room is changed by air-conditioner, but also the room temperature in a kitchen. This is because of the house design of iHouse. There is no partition or wall between the living room and the kitchen. Thus, heat energy can be transferred directly. Increase or decrease of room temperature in the kitchen relies on the changes of the room temperature in the living room.

With the goal of EMS, our proposed home simulation simulates the electricity consumption based on the human activity schedule. Figure 8 shows the energy consumption of each home appliance. Human simulator generates the human activity, and then send the message to home appliance simulator for activating the home appliance. After the home appliance is activated, the home appliance simulator will send the wattage and time operation to the electric power consumption simulator to calculate the electricity consumption. According to the results, we can monitor the use of electricity time by time. Thus, it is easy to avoid and alert the resident when the critical loads occur. Moreover, these results can be used in further circumstances. For example, the system can suggest the resident to change the time for charging the car battery from day time to night time based on time-of-use pricing or critical peak pricing.

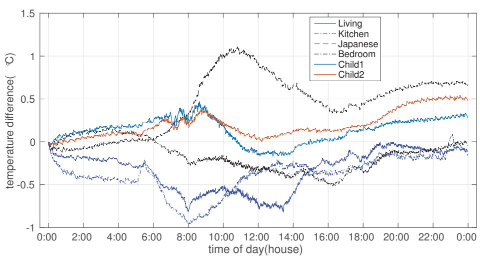

Figure 6: Temperature difference in each room

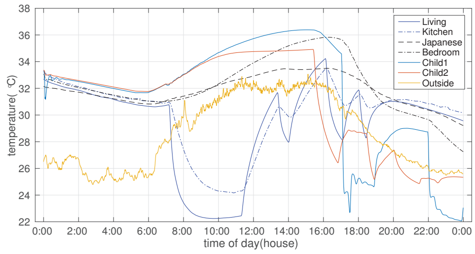

Figure 7: Simulated temperature results in each room

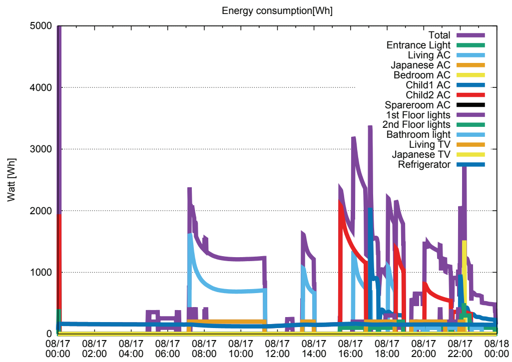

Figure 8: Electricity consumption of each home appliance

6 Conclusion and Future Works

This paper presented the home simulation for energy management system, which can simulate the thermal environment and the electricity consumption. Five elements: house, home appliance, physical environment, electric power, and human were investigated for implementing the home simulation. Five simulators were developed for identifying each element. Furthermore, network interface, called SimHome library, was built for interoperation among the five simulators. With the abilities of our proposed home simulation, the results of comparative experiment illustrated the high performance of this simulation in term of thermal energy simulation. The temperature difference between the measured temperature results and the simulated temperature results were maximum 1.2 degrees Celsius. In addition, the proposed home simulation can be able to simulate the electricity consumption for monitoring and analyzing the use of home appliances. The electricity consumption was generated based on the human activity schedule, which was trained from NHK survey.

Although the proposed home simulation can generate the results both the thermal energy and the electricity consumption, some parts of the home simulation need to be improved. For instance, demand response concept should apply in the home simulator. Consumers play a vital role in the operation of reducing grid by reducing or shifting the home appliance usage when the peak load occurs.

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