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Citation	Lecture Notes in Computer Science, 7910: 159-166
Issue Date	2013
Type	Journal Article
Text version	author
URL	http://hdl.handle.net/10119/12088
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Description	

Building high-accuracy thermal simulation for evaluation of thermal comfort in real houses

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Abstract. Thermal comfort is an essential aspect for the control and verification of many smart home services. In this research, we design and implement simulation which models thermal environment of a smart house testbed. Our simulation can be used to evaluate thermal comfort in various conditions of home environment. In order to increase the accuracy of the simulation, we measure thermal-related parameters of the house such as temperature, humidity, solar radiation by the use of sensors and perform parameter identification to estimate uncertain parameters in our thermal model. We also implement a communication interface which allows our simulator to communicate with other external simulators. Experimental result showed that our simulation can achieve high accuracy when compared with actual measurement data.

Key words: Thermal environment, Smart house, Simulation

1 Introduction

Smart home services nowadays can bring to us a comfortable living environment, but also consume a large portion of electrical energy. Nowadays, the introduction of renewable energy sources, networked appliances and sensors to smart homes gives us the ability to increase energy efficiency in houses. Environment data gathered by sensor networks, such as temperature, humidity, solar radiation can be sent to a service provider, which uses the data to control the operation of energy sources and networked appliances. For example, we can control the opening and closing of windows as well as the operation of air conditioning system to optimize the amount of consumed energy [1].

Verification of smart home services by both simulation and experiments is essential since simulation can save time and resources for system development, while experiments can verify the operation of real systems. Since there are many home services targeting to improve thermal comfort for residents, it is essential to develop a high-accuracy thermal simulator which can simulate the behavior of thermal environment of real houses at different conditions. Furthermore, the simulator should have the ability to communicate with other simulation programs of networked control systems.

There are many thermal simulators for buildings such as DOE-2 [3], EnergyPlus [4]. However, since these simulators are used for the design of buildings, they require a large number of detailed thermal parameters to be specified. In the case of modeling real houses, many parameters are unknown and needed to be identified by the use of measurement data of external and indoor thermal environment. Several works [5, 6] 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. These parameters are essential since they have a significant affect on the change of room temperature.

In this research, we build a thermal model for a smart house testbed, which utilizes external environment data measured by sensors as input. Our model calculates the change of room temperature by calculating heat fluxes coming in and escaping a room based on a number of physical models. We implement our thermal model in MATLAB/Simulink environment and utilize Simulink Design Optimization toolbox to identify uncertain parameters in our thermal model, based on measurement data of room temperature. Comparison of experimental results with simulation results shows that our simulator has high accuracy with the error within 1 degree centigrade. We also design an communication interface to interact with other external simulators, which can be used for verification of smart home services.

This paper is organized as follow. In Section 2, we describe simulation object and simulation model. The next section describes the design of our simulator. Section 4 shows validation results of our simulation. Section 5 concludes the paper.

2 Simulation model

2.1 Simulation object

We perform our simulation targeted on a testbed house for smart home services, called iHouse, which is located at Ishikawa prefecture, Japan. It is a typical 2-floor Japanese-style house with 15 rooms (Fig. 1). Appliances in iHouse include air conditioners, wattmeters and sensors, which are connected to the network via ECHONET protocol [7]. A home gateway which allows communications between home network and service providers is set up in the house. Furthermore, house furniture and equipment is installed in the house to allow people to live there.

Since the thermal environment of a house is heavily dependent on the outside environment, we use a number of sensors to monitor external environment. They include a sensor for measuring temperature and humidity, an anemometer for measuring wind speed and direction and a solar heliograph for measuring actual sunshine duration, which is defined as the time that direct insolation is over 120W/m^2.

We measure room temperature and humidity to estimate simulation parameters and evaluate simulation results. Among 15 rooms of iHouse, 11 rooms have

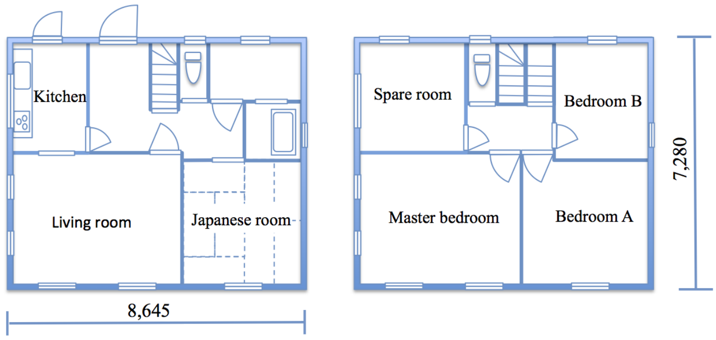

Fig. 1. Structure of iHouse

temperature and humidity sensors. 8 temperature and humidity sensors are installed in each of these rooms, 4 sensors at 4 higher corners and 4 sensors at lower corners.

2.2 Thermal model

In our model, we assume that the temperature of a room is uniform in all areas of the room. The room temperature T is calculated as follows.

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

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. We model several kinds of heat fluxes as follows.

- Conduction heat flux: We use unsteady-state heat transfer model to calculate conduction heat flux through a wall. This model can take into account the fast change of temperature at surfaces of walls.
- Solar radiation heat flux: We estimate direct solar radiation based on measured data of a solar heliograph and use Reindl direct-diffuse splitting model [11] to estimate diffuse radiation.
- Device heat flux: Device heat is assumed to be constant.
- Air conditioner heat flux: We use PID control to model the control of air conditioning units at each room.

Conduction heat flux We calculate conduction heat flux through windows under steady-state heat transfer conditions as follows.

$$Q_{cond} = U_{win}.A_{win}.(T_o - T_r)(W) \quad (2)$$

Here, U_{win} and A_{win} are the heat transmission coefficient (W/m^2K) and the area (m^2) of a window, T_o and T_r are outside temperature and room temperature(K).

In the case of walls, we calculate conduction heat flux under unsteady-state heat transfer conditions since the temporal and spatial change of temperature inside walls can not be ignored. Due to the work of Milatas et. el [8], the change of temperature at each surface of a wall can be expressed as a triangle wave and Laplace transformations can be used to solve one dimensional heat equation (4) of the wall.

$$C_v \frac{dT}{dt} = \lambda \frac{d^2T}{dx^2} \tag{3}$$

As results, we obtain response factors Z_j and Y_j of the wall and calculate the heat flux through the wall as follows.

$$Q_{cond}(t) = A_{wall}(\sum_{j=0} Y_j T_o(t - j\delta_T) - \sum_{j=0} Z_j T_r(t - j\delta_T))(W) \tag{4}$$

Here, A_{wall} is the surface area of the wall, $T_o(t-i\delta_T)$ and $T_r(t-i\delta_T)$ are surface temperatures of the wall at time $t - i\delta_T$, δ_T is a time interval.

Since external walls absorb solar radiation and become hot during daytime, external surface temperatures of these walls are calculated by solving the heat balance equation at surfaces of walls.

$$Q_s + Q_a = Q_{conv} + Q_r + Q_{cond} \tag{5}$$

Here, Q_s is absorbed direct and diffuse solar radiation heat flux, Q_a is absorbed radiation heat flux from external air and from ground, Q_{conv} is convection heat flux between external surface and outside air, Q_r is radiation heat flux from wall surface and Q_{cond} is conduction heat flux into the wall.

Convection heat flux between external surface and outside air depends on the velocity of wind and is calculated due to the work of Ito et. al [9]

$$h = 18.6 v^{0.605} (W/m^2K) \tag{6}$$

Here, v is wind velocity near the surface of the wall.

Solar radiation heat flux Solar radiation heat flux Q_r through a window is calculated as follows.

$$Q_r = (ID.\lambda_{ID} + IS.\lambda_{IS}).A_{win} \tag{7}$$

where ID is direct radiation, IS is diffuse radiation, $\lambda_{ID}, \lambda_{IS}$ are solar radiation heat gains of the window .

We estimate the direct radiation with the use of actual measurement data, provided by the solar heliograph. Recent researches attempts to estimate direct radiation and diffuse radiation based on actual sunshine duration but the estimation is performed in an hourly basis [10]. The solar heliograph is a solar battery which voltage is 20mV when the direct insolation is 120W/m^2. We measure the highest voltage during the summer and estimate the direct insolation at that time. We assume that the voltage characteristic of the solar heliograph

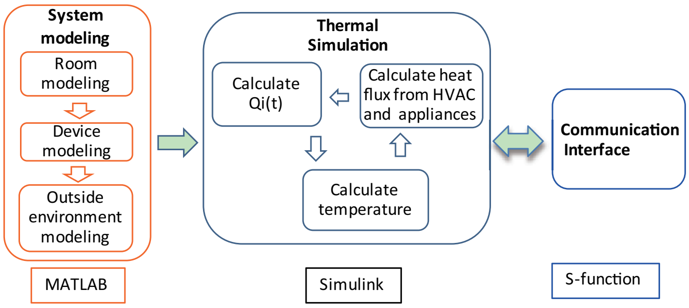

Fig. 2. Structure of thermal simulator

is expressed as a line which passes through the above points and estimate direct insolation based on this assumption.

Diffuse solar radiation is calculated based on Reindl direct/diffuse splitting model [11]. In this model, the ratio of diffuse solar radiation and global solar radiation is estimated based on clearness index, solar altitude angle, ambient temperature, relative humidity. Since the direct solar radiation I_d is calculated based on diffuse solar radiation I_s, global solar radiation I_g and solar altitude angle h, we can estimate diffuse solar radiation to fit with the value of direct solar radiation.

Solar radiation heat does not warm up room air immediately but it warms up curtains, ceiling and floor, which then warm up room air. Therefore, we calculate the heat flux caused by solar radiation based on the historic values of solar radiation.

$$Q_r(t) = \sum_{j=0}^{n} Q_r(t - j\delta_T)\eta_j \tag{8}$$

where $Q_r(t - j\delta_T)$ is the solar radiation heat flux through the window at time $t - j\delta_T$ and $\eta_j, j = 0..n$ are response factors.

3 Simulator design

Our simulator includes 3 modules (Fig. 2).

– House modeling: iHouse is modeled as a house which includes a number of rectangular rooms and each room contains a number of walls and windows. The module first inputs parameters related to thermal characteristics of walls and windows. It then uses as input sensor data regarding temperature, humidity, wind velocity and voltage of solar heliograph and calculates direct and diffuse solar radiation, surface temperature of walls and windows due to each model.
– Thermal simulator: This module calculates heat flux escaping and entering each room, and calculate room temperature for each room of the house using equation (1).

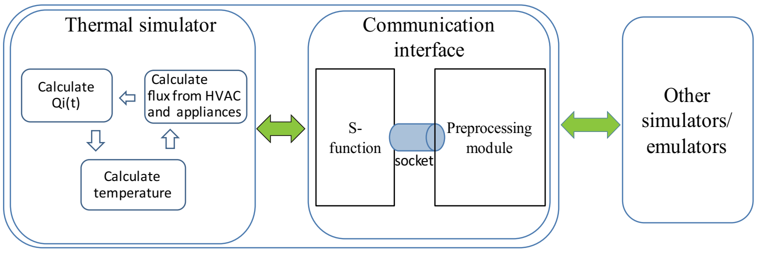

Fig. 3. Design of communication interface

– External interface: This module will receive control information of air conditioner, windows and other appliances from and send room temperature to external programs.

We implement our simulator in MATLAB/Simulink environment which supports user-friendly interface and the ability of analyzing simulation results.

In our thermal model, there are several thermal characteristics of rooms, those are unsettled such as furniture's specific heat, solar heat gain of windows, wall surface's heat radiation and absorbance. Estimation models of external weather such as direct solar radiation, diffuse solar radiation and convection heat transfer coefficient also have margin of errors[12, 13]. Therefore, parameter identification is required to improve the accuracy of simulation results.

We use Simulink Design Optimization toolbox[14] to identify uncertain parameters of the model. The toolbox runs the thermal model a number of times and adjusts parameters based on an optimization algorithm such as trust region reflective algorithm. Since the running time depends heavily on the size of the whole model and the number of parameters to be identified, we perform parameter identification for each room and identify a number of representative parameters instead of identifying all uncertain parameters. For each room, we identify from 6 to 10 parameters.

We also use S-function with socket communication to implement communication interface (Fig. 3). A preprocessing module is implemented to receive and process input data from external simulators. This module allows complicated interactions between thermal simulator and external simulators. Data consistency between our simulator and external programs is kept by a simple clock synchronization mechanism.

4 Validation

We have performed data measurement and simulation to validate the accuracy of our model and simulator. 4-day experiment data in July 2012 and 4-day experiment data in October 2012 were used to perform parameter identification for each room. The measurement interval of external environment was 10s. The measurement interval of room temperatures was 120s. We then validated the

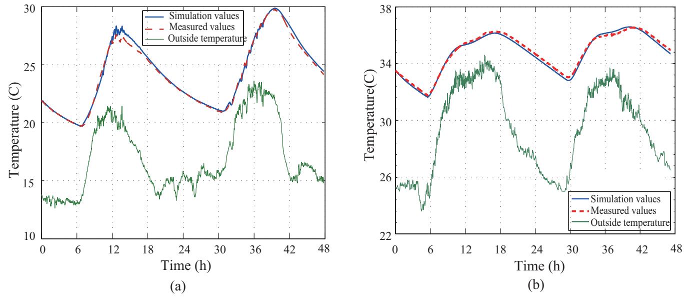

Fig. 4. Simulation and measurement results for 2-day experiment at master bedroom in autumn weather and at bedroom B in summer weather (air conditioner is not operated)

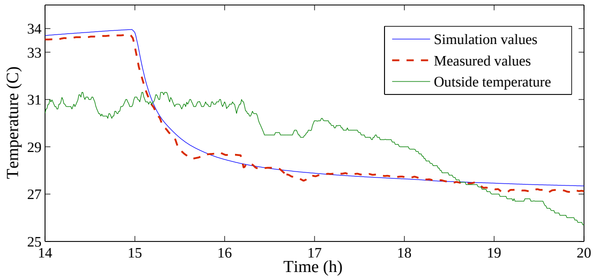

Fig. 5. Simulation result and measurement result of cooling experiment at bedroom B

simulation results by performing simulations of all rooms using identified parameters.

Figure 4 shows the validation of our model using identified parameters. 2-day experiment data in autumn weather and 2-day experiment data in summer weather are used to evaluate simulation results. Here, air conditioners are not operated. As result, the differences between simulation results and measurement results are maximum 0.9 degree centigrade. The difference is high in the room which temperature changes slightly and is low in the room which temperature changes heavily.

Under the condition that the air conditioner is operated, the difference between simulation values and measured values is maximum 1.0 degree centigrade (Fig. 5). Control information of air conditioner is sent to the simulator via the communication interface.

5 Conclusions

In this research, we have built a thermal simulator which models an experimental house for smart home services. Thermal-related parameters of the house are measured by the use of sensors and a number of physical models were utilized to calculate heat flux coming from external environment. Furthermore, we perform parameter identification to identify uncertain parameters in our thermal model. Therefore, our simulator can achieve high accuracy when compared with actual measurement data. We also design an communication interface, which allows our simulator to communicate with external simulation programs.

In future, we will extend our simulator to model other experimental houses and develop verification programs for smart home services.

Acknowledgement

This work is partly supported by the joint research project between Japan Advanced Institute of Science and Technology (JAIST) and National Institute of Information and Communications Technology (NICT)

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