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Simplified Linear Models for Predictive Control of Advanced Solar Homes with Passive and Active Thermal Storage

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Simplified Linear Models for Predictive Control of Advanced Solar Homes with Passive and Active Thermal Storage

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ABSTRACT

This paper investigates the use of simplified linear transfer function models −obtained from system identification of results obtained with building simulation tools− for the development of control strategies in solar homes having passive and active thermal storage capabilities. Solar homes are defined here as those using solar radiation to meet a considerable fraction of their energy needs with solar heat gains and active solar energy systems (such as PV panels and solar thermal collectors). Advanced control strategies can be used in these houses to manage the highly variable solar resource, by taking advantage of passive storage in the building's thermal mass and active thermal energy storage systems. Although detailed building simulation models can be used directly for testing control strategies, this approach can be quite computationally intense and time consuming. The methodology presented here offers a practical alternative, which provides insight into the importance of different design and control parameters and facilitates the use of software and tools designed specifically for testing control algorithms.

1. INTRODUCTION

Advanced solar buildings use both passive solar design and active solar technologies to achieve high levels of energy efficiency and even become net energy generating systems (Candanedo and Athienitis, 2010). Solar houses typically have one or more of the following features:

- Integrated design; a global, coherent plan for the interaction of the energy subsystems among themselves and with the building envelope. Devices and components often perform more than one function.
- Passive solar design: high quality building envelope, large and properly oriented fenestration intended for solar gain collection, properly sized overhangs and significant thermal mass.
- Building-integrated renewable energy technologies (building-integrated PV, solar thermal collectors, etc.).
- An HVAC system that contributes to the dynamic control of the building's thermal mass.
- Motorized blinds or advanced fenestration permitting control of solar gains.
- Advanced control systems (e.g., "smart home" technologies).

Accurate physical models are necessary for developing these houses. It has been shown that simple thermal networks can provide a mathematical representation of a residential building with a reasonable level of accuracy (Athienitis *et al.*, 1990; Fraise *et al.*, 2002; Kämpf and Robinson, 2007). A linear-time invariant (LTI) thermal network can be used to obtain transfer functions between relevant inputs and outputs which can then be used for control applications (Athienitis *et al.*, 1990). However, the problem of creating a simplified thermal network model from first principles is to ensure the reliability of the model when compared to more complex tools. This paper presents a methodology to develop control strategies for solar houses. This methodology is based on transfer functions obtained from EnergyPlus (Crawley *et al.*, 2000) models. It is applicable to models created in any welldocumented building simulation package. This method has advantage of providing reasonably accurate models (since they are obtained from a benchmark building simulation tool), while offering the advantage of simplicity.

2. METHODOLOGY

2.1 Summary of the Methodology

The methodology proposed here can be summarized as follows:

1. A model of the building is created with a building simulation tool.
2. Artificial profiles of solar radiation, exterior temperature, etc. are used to obtain the response of the variable of interest (mean air temperature, mean radiant temperature, operative temperature). The response of to each input is found independently of the others.
3. Transfer functions, either in the s-domain (Laplace transfer functions) or in the z-domain (discrete transfer functions) are identified.
4. A simplified model is created with the transfer functions obtained.
5. A software tool suitable for design and testing of control strategies (e.g., MATLAB/Simulink) can then be used to test supervisory control strategies (blind control, management of passive and active TES systems) and lower level control strategies.

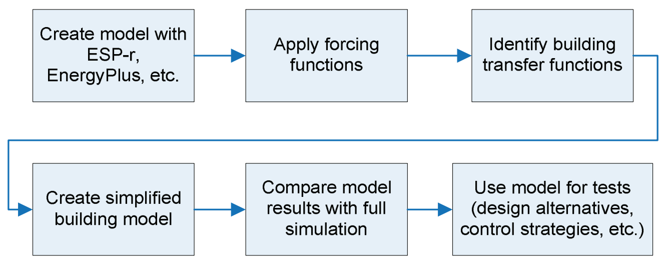

Figure 1. Methodology flowchart.

2.1 Case Study

To illustrate the use of transfer functions for a solar house, a simple case will be discussed. Figure 1, a 7.5 m x 5 m x 3 m shed, was created using SketchUp. The Open Studio (NREL, 2009) plugin for SketchUp was used to create the basic geometry corresponding to an IDF (input file) for EnergyPlus (Crawley *et al.*, 2000). The remaining data was introduced directly by modifying the input file. This shed is a well-insulated building, with nearly R-50 (RSI 8.8) in its walls and R-55 (RSI 9.7) in its roof-ceiling. This shed has a concrete slab floor 15-cm thick, on top of 150 mm of insulation board R-28.5 (RSI 5). The only fenestration is a large south-facing, argon-filled, triple-glazed window with two low emissivity coatings. The south-facing roof has a 45° slope. The infiltration is defined by a constant value of 0.25 ACH. No internal gains are considered. A radiant floor heating system, which could be electric or hydronic, is embedded at the bottom of the floor's concrete slab.

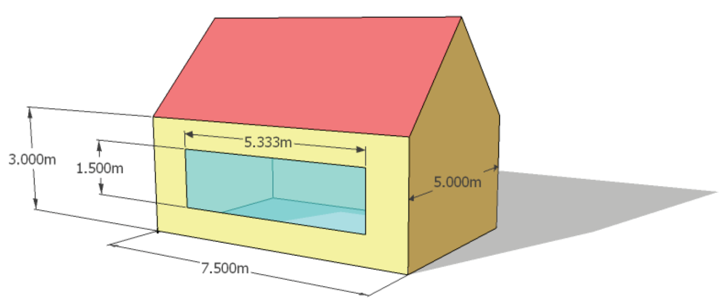

Figure 2. Test building used in the simulations (SketchUp image).

To find the transfer functions, the following assumptions were made:

- Thermal phenomena can be modeled satisfactorily by considering it as a linear-time invariant (LTI) system. Therefore, the superposition principle applies.

- The only variables (inputs) influencing the indoor temperature are: (a) the exterior temperature; (b) solar radiation; and (c) the heat delivered by the radiant floor heating system.
- The zone mean air temperature will be the only output variable considered.
- All other weather variables (radiation to the sky, losses to the ground, etc.) are neglected.

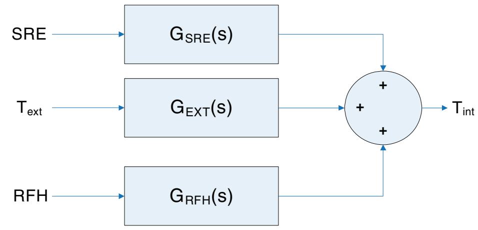

Figure 3. Simplified transfer function model for the building under study.

To obtain the transfer function corresponding to the effect of solar radiation, a Montréal EnergyPlus weather file was modified by making the exterior dry-bulb temperature through the year equal to 0 °C, without affecting the rest of the variables. A sequence of days was then repeated, while keeping the radiant floor heating off. The total *solar radiation transmitted through the windows* was chosen as the input vector. Fig. 4 shows the results for the zone mean air temperature under these conditions.

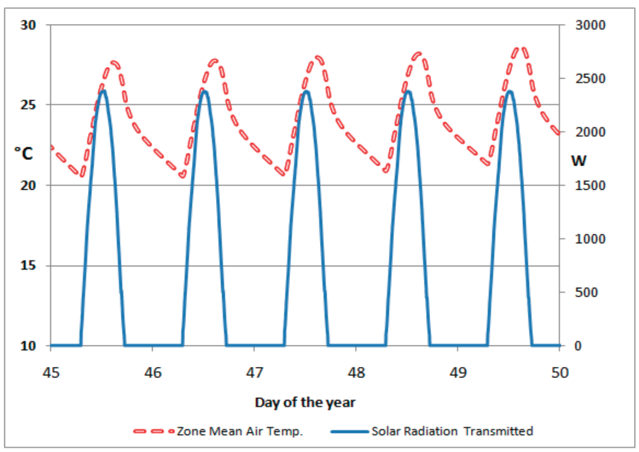

Figure 4. Response of the zone air temperature to solar radiation entering the room.

The data presented in Figure 4 were introduced in MATLAB's System Identification Toolbox (Lennart, 2010) as two vectors, corresponding respectively to the input (solar radiation transmitted) and output (zone mean air temperature). This Toolbox permits choosing several equivalent discrete (z-transform) and continuous (Laplace transform) approximations for the transfer function between variables. State-space representations can also be found. The user can select the order of the model. In this case, third order Laplace transfer functions were selected for exterior temperature and solar entering radiation. The transfer function corresponding to indoor temperature/solar radiation transmitted, $G_{SRE}(s)$, was approximated by the following polynomial ratio:

$$\tilde{G}_{SRE}(s) = \frac{2.27\times10^{-6}s^2 + 4.21\times10^{-10}s + 3.12\times10^{-14}}{s^3 + 4.17\times10^{-3}s^2 + 2.48\times10^{-7}s + 7.06\times10^{-13}} \text{ [K/W]} \quad (1)$$

To find the transfer function between exterior temperature and indoor temperature, the Montréal EPW (EnergyPlus weather) file was modified by setting solar radiation equal to zero and by repeating a sequence of 5 days. The selected sequence was chosen to include strong temperature fluctuations. Again, the floor heating system was inactive. The obtained results are shown in Fig. 5.

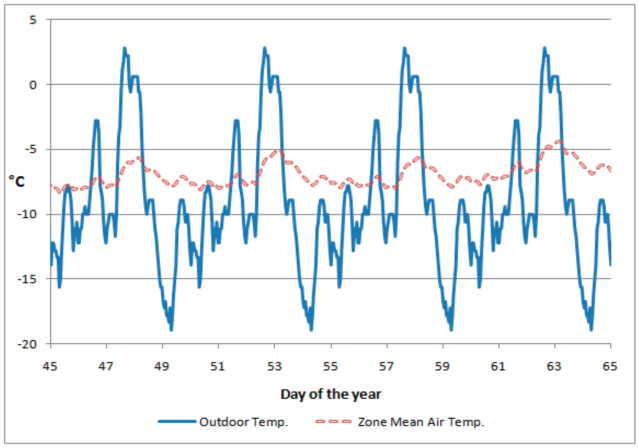

Figure 5. Response of the zone air temperature to outdoor temperature.

In this case, the approximate transfer function for the exact transfer function $G_{EXT}(s)$ is given by:

$$\tilde{G}_{EXT}(s) = \frac{2.63\times10^{-5}s^2 + 7.53\times10^{-9}s + 3.00\times10^{-13}}{s^3 + 1.62\times10^{-4}s^2 + 1.03\times10^{-7}s + 3.78\times10^{-13}} \text{ [K/K]} \quad (2)$$

Finally, another modification of the Montréal weather file was made to keep solar radiation and exterior temperature at 0 °C. Then, a simple control scheme was chosen to provide a heat input to the floor slab. The response of the indoor air temperature and the heat input curve are presented in Fig. 6.

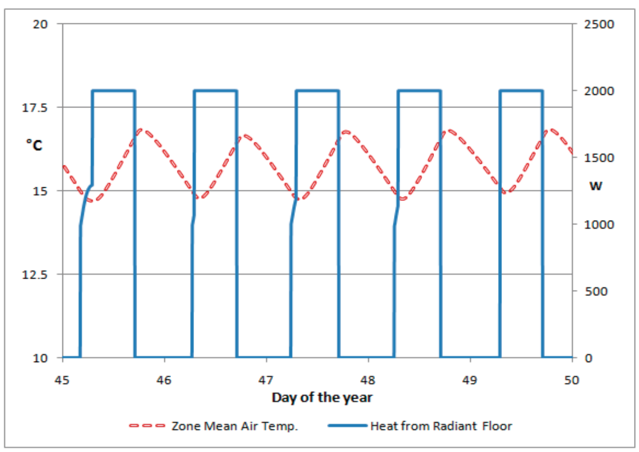

Figure 6. Response of zone air temperature to heat input from radiant floor.

As in the previous cases, an approximate transfer function was found relating the indoor temperature response to the heat input from the radiant floor. The coefficient of s in the denominator corresponds to a time constant of 118.2 hr.

$$\tilde{G}_{RFH}(s) = \frac{0.01836}{1 + 4.254\times10^{5}s} \text{ [K/W]} \quad (3)$$

The use of Laplace transfer functions facilitates the study of the response of the system in the frequency domain. A controller in real conditions will likely make use of equivalent z-transfer functions, suitable for implementation in a digital controller (Underwood, 1999).

3.1 Comparison with EnergyPlus Results for "Free Floating" Condition

A validation of the transfer function model was made by comparing the response of the transfer function model with that obtained with EnergyPlus under free floating conditions (Fig. 7.a). Simulink, MATLAB's graphical interface for dynamic simulation was used for this purpose (Husaundee and Visier, 1999; Riederer, 2005). Results obtained (Fig. 7.b) support the use of a simplified transfer function model as a suitable simulation method.

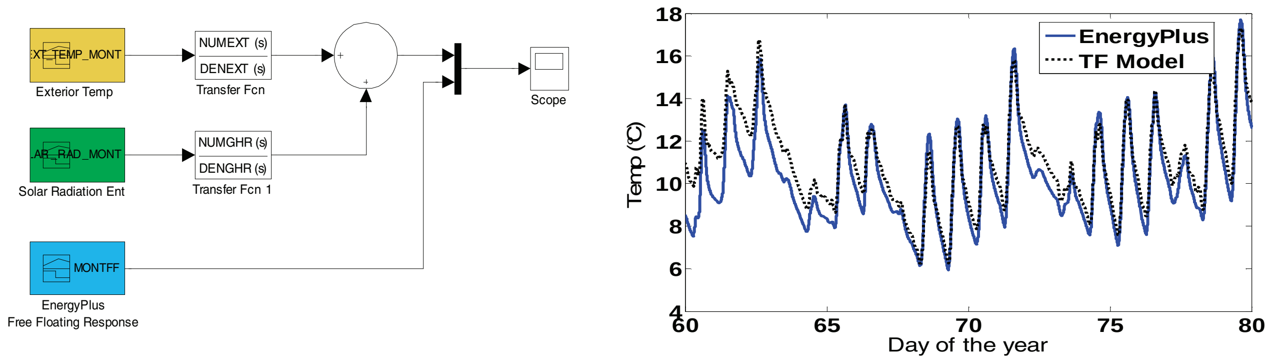

Figure 7. (a) Simulink representation of the model under "free-floating"conditions; (b) Comparison of the EnergyPlus and TF model outputs.

3. CONTROL APPLICATIONS OF THE TRANSFER FUNCTION MODEL

3.1 Applications for Local-Loop Control

Building controls may refer to (a) the supervisory control level, in charge of establishing set-points and desired states and (b) lower level local-loop control, whose role is to closely track the desired set-points (ASHRAE, 2007). Local-loop control may be particularly difficult in houses with large passive solar gains and significant thermal mass, because the slow response of the building together with the significant influence of solar radiation on indoor temperatures makes it difficult to track a reference temperature (Athienitis *et al.*, 1990). The use of a simple transfer function model facilitates testing advanced control strategies. For example, Model Predictive Control (MPC) (Rossiter, 2003) is a technique developed originally for control of chemical engineering processes, which are characterized by slow responses. Unlike traditional control (such as ON/OFF or PID) which *reacts* to measured differences between the output and the reference, MPC uses expected disturbances (solar radiation and temperature) to adjust *current and future values* of the manipulated variable, the heat delivery rate (see Fig. 8). The availability of online weather forecasts and micro-controllers facilitates the implementation of MPC in solar houses (Chen, 2002).

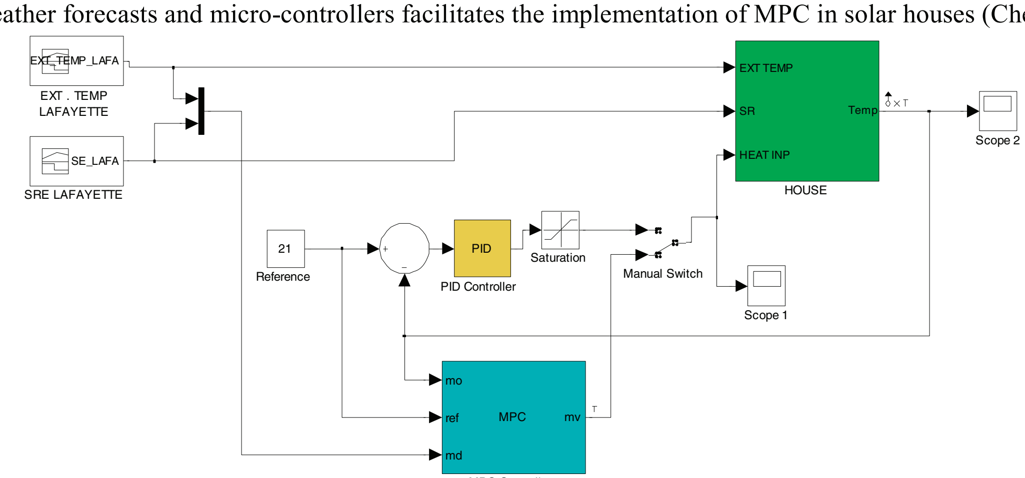

Figure 8. Simulink model permitting switching between a MPC and PID controllers.

Simulations were performed with weather data from the EPW file corresponding to West Lafayette, IN. Two different controllers were implemented in Simulink: an MPC controller and a PI controller. The MPC controller uses a linear model (created with the three transfer functions obtained) to manipulate the radiant floor heating system. The output of the radiant floor heating system is restricted to a maximum of 2 kW in both cases, and there is no artificial cooling. The MPC controller performs better than the PI controller (Fig. 9); sizeable fluctuations are nevertheless observed.

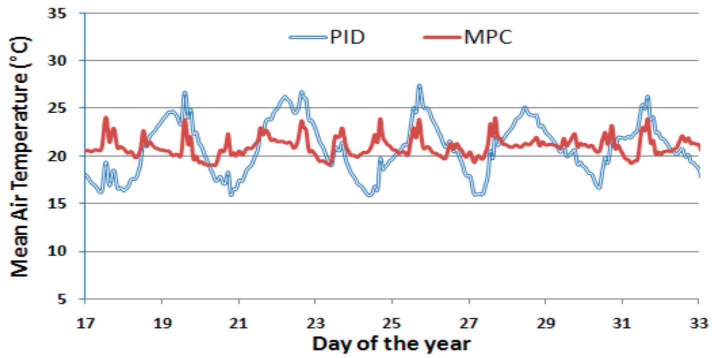

Figure 9. Comparison of the performance of MPC and PID (k_P = 500 W/K, k_I = 50 W/K·s) controllers.

The case presented here is intended as a proof of concept. Several strategies can be tried to improve the system's performance. Among them: (a) introducing the control of a motorized shading device as another manipulated variable by the MPC controller; (b) using a variable set-point throughout the day (sinusoidal, linear ramps, etc.).

3.2 Supervisory Control Application – Active TES and its Interaction with the Building

In an advanced solar building, transfer function models can also help to optimize the use of thermal energy storage systems and their interaction with the building's thermal mass. The following example, corresponding to work still in progress, is presented to illustrate a possible application. Control strategies applied to a similar system, based on the use of weather forecast information, have been presented elsewhere (Candanedo and Athienitis, 2008, 2010).

It is assumed that the building shown in Fig. 1 has a building-integrated photovoltaic/thermal (BIPV/T) system on its south roof. A BIPV/T system utilizes a flow of exterior air through a channel under PV panels to cool them, thus recovering useful thermal energy (Bazilian *et al.*, 2001). The air leaving the BIPV/T channel is often considerably hotter than the exterior. For a roof of the dimensions shown in Fig. 1, and a flow rate of 750 CFM, the exit air is about 20-30 °C warmer than outdoor air under typical clear sky conditions. Despite this significant temperature rise, this air may not be hot enough for direct space heating in cold climates. However, the BIPV/T air can be used as the source of an air-source heat pump. Since the BIPV/T-assisted heat pump can only be used during a brief period each day, storing thermal energy is essential. Thermal energy storage (TES) can be carried out either in the building's thermal mass (passive storage) or with active thermal storage systems (water tanks, PCM materials, thermochemical storage, etc.). It is assumed that the TES system used in this case is a 1000 L water tank (Fig. 10).

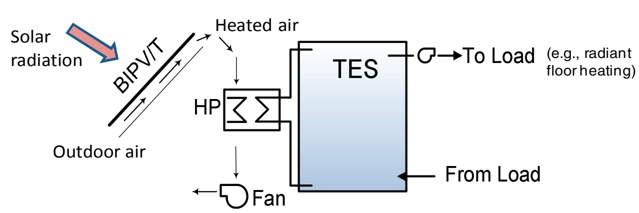

Figure 10. Schematic of BIPV/T-assisted air-source heat pump linked to a TES water tank.

In the system presented above, the thermal "state of charge" is determined by the temperature of the TES tank and the energy stored in the building's thermal mass: Let's assume that the temperature of the house is already given by the MPC controller. Let x be the temperature of the TES tank. The supervisory control problem consists of providing a sequence of desired values for x.

Although a naïve approach may be to keep the tank "fully-charged" at all times (i.e., at maximum temperature) in order to satisfy the energy requirements of the load, under these conditions the COP of the heat pump would be low. The COP of the heat pump is also a function of the BIPV/T air temperature, which also depends on the air flow rate and weather variables (solar radiation, exterior temperature, etc.). Optimal control techniques, which have received significant attention for large commercial buildings with passive and active storage (Braun, 1990; Henze *et al.*, 2005), may also be applied to the specific problem of advanced **solar** homes, by selecting an objective function J (e.g., total energy consumption, total cost or maximum peak load). If the total energy consumed by the heat pump is selected as the objective function, J is then given by:

$$J = \int_0^T P_{HP}(t)dt \tag{4}$$

The optimal control problem would then consist of finding the set-point sequence $\{x_1, x_2, \ldots x_n\}$ such that J is minimized over the control horizon T. To accomplish this, it is necessary to predict how much heat will be required by the heating system, and how much heat can be collected from the roof. As shown in the previous section, the simplified transfer function model can be use to calculate the energy extracted from the TES tank over the control horizon. Online weather forecasts (or in this particular case, the EPW file) can be used to predict the radiation on the roof. A mathematical model is used to estimate the output of the BIPV/T system. The "cost function" $P_{HP}(t)$ corresponds to the power consumption of an air-water heat pump and is based on manufacturer's data. Several optimal control techniques can be applied to select the sequence of tank set-points. In this case, dynamic programming is used to find the "optimal path" that satisfies the required load (heat delivered to the floor, as estimated by the MPC controller) while minimizing the energy consumed by the heat pump.

Fig. 11 shows an example for a 48 hr control horizon. As shown in the figure, the optimal control path predicts that fairly low set-points (30-35 °C) will accomplish the required task at significantly lower energy consumption by the heat pump (9.8 kWh versus 16.1 kWh for an arbitrarily chosen set-point curve). It is worth mentioning here that the set-point curve increases when the high solar radiation values are expected.

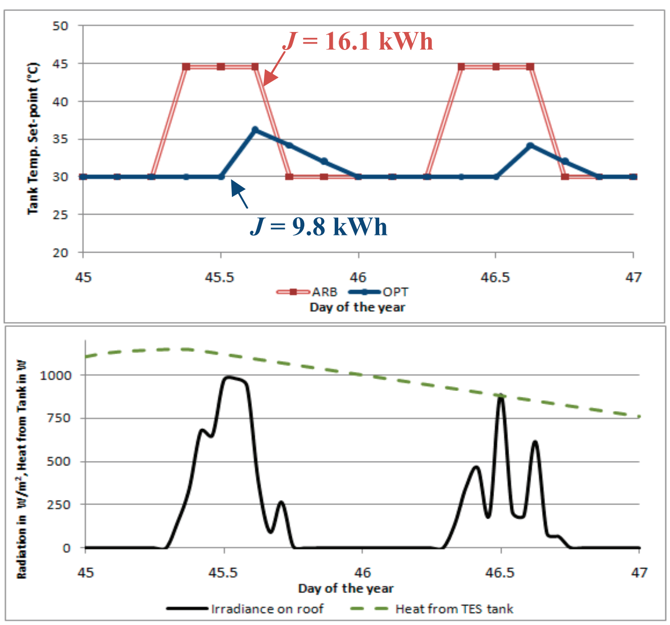

Figure 11. (a) Arbitrary and optimal set-point paths for the TES tank. (b) Corresponding irradiance on roof (W/m²) and heat rate (W) from the TES tank into the radiant floor as calculated by the MPC controller.

4. CONCLUSIONS

Simple transfer function models, created through system identification of building simulation software results, have been presented as a practical methodology for developing and testing control strategies for advanced solar homes. It has been shown that these transfer functions can satisfactorily model the response of a building with significant solar gains. Control strategies may include both supervisory control, based on the optimal selection of set-point sequences, and lower level control (such as model predictive control).

NOMENCLATURE

BIPV/T	Building integrated PV/thermal	
EPW	EnergyPlus weather file	
G	Exact transfer function	
$\tilde{G}$	Approximate transfer function	
IDF	EnergyPlus input file	
J	Objective function	
LTI	Linear time invariant system	
MPC	Model predictive control	
P_{HP}	Electric power	(W)
TES	Thermal energy storage	
x	System state variable	(°C)

Subscripts

CP	Circulating pump
EXT	Exterior temperature
fan	Variable speed fan
HP	Heat pump
RFH	Radiant floor heating
SRE	Entering solar radiation

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