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Black-box modeling of residential HVAC system and comparison of gray-box and black-box modeling methods

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ABSTRACT

In this article, black-box models of the residential heating, ventilation and air conditioning (HVAC) system are developed. The data of the input and output of the system is measured and the models of the energy recovery ventilator (ERV), air handling unit (AHU), buffer tank (BT), radiant floor heating (RFH) and ground source heat pump (GSHP) are developed using the system identification techniques in Matlab®. The developed models include models based on multiple-input and multiple-output (MIMO) artificial neural network (ANN), transfer function (TF), process, state-space (SS) and autoregressive exogenous (ARX) ones of each HVAC subsystem (ERV, AHU, BT and RFH). The gray-box models of the same HVAC subsystems were developed in [1] which are also compared with the black-box models developed in this article. The models were compared visually and analytically. Ranks of the models were calculated based on their relative performance. It was found that the ANN outperforms the other modeling methods followed by the ARX, TF, SS, process and gray-box models respectively.

1. Introduction

Heating, ventilation and air conditioning (HVAC) systems consume about 40% of the total energy in a building [2,3]. The energy consumption of the system can be reduced if it can be predicted accurately and appropriate energy conservation strategies, e.g., thermal storage in the building mass [4] or floor heating mass [5], passive solar gains [5], thermal storage in tank water [6,7], temperature reset during unoccupied hours [8,9], night setbacks, pre-cooling during off-peak periods and set-point changes during peak hours [10,11], optimum start and stop times [12], ventilation control [13,14] and economizer cycle control [9,15,16] are applied. Advanced controllers [17] e.g. classical PID [18,19], nonlinear [20], robust [21], optimal [22], model predictive [23–26], fuzzy logic [27–30], neural network [8,31–34] adaptive fuzzy [35], adaptive neuro [8], and fuzzy PID [30] can also be implemented to predict the energy consumption and take appropriate actions to reduce energy consumption. The performance of the controllers depends largely on the accuracy of the system models and the processes being controlled. Therefore the development of accurate models is necessary which perform well under the wide range of operating conditions and are able to cope with the nonlinear behavior of the system.

According to the review of modeling methods for HVAC systems in [36], the researchers have developed several methods such as white-box models [37,38], black-box models [23,32,39–43] and gray-box models [44–47] to model the behavior of the HVAC systems. The white-box models require the understanding of the system physics and use the manufacturer supplied parameters for modeling the system dynamics. The white-box models have good generalization capabilities but poor accuracy compared to the black-box models. The black-box models are developed by measuring the data of the system input and output and fitting a mathematical function to the data. The development of black-box models does not require the understanding of the system physics and they have high accuracy compared to the physics-based models though they suffer from the poor generalization capabilities. A balance between the good generalization capability and high accuracy is provided by the gray-box models which use the physics based white-box model as the mathematical structure and measured data to estimate the parameters of the models. As a result, gray-box models require more effort to develop, have good generalization capabilities compared to black-box models, and demonstrate higher accuracy compared to the white-box models.

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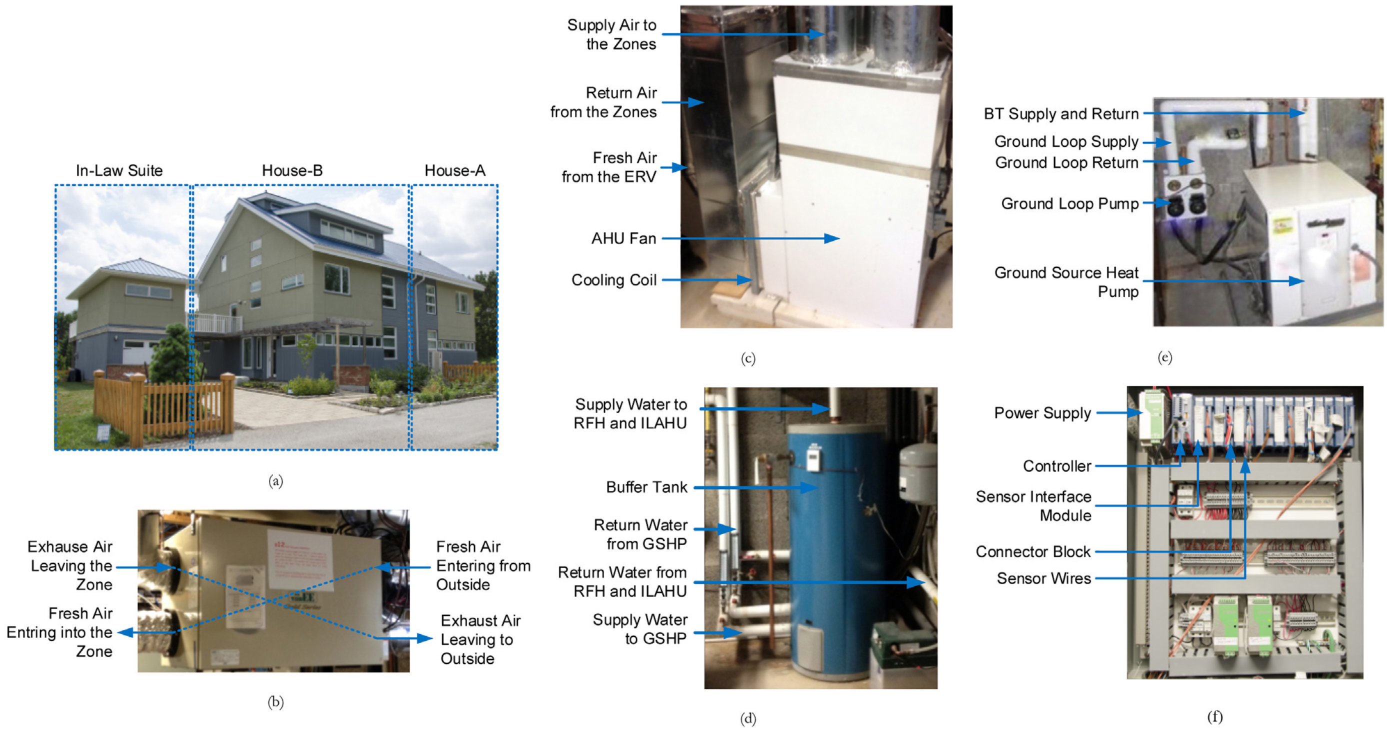

Fig. 1. (a) Front view of the TRCA-ASH, (b) ERV, (c) AHU, (d) BT, (e) GSHP and (f) DAQ system.

The organization of the article is as follows. In Section 2, system description is provided explaining the residential HVAC system under research. In Section 3, the details regarding the developed models are provided. In Section 4, two methods for comparison of the models, i.e., visual and analytical methods are provided and the models are ranked based on their overall performance. At the end, the conclusions are drawn and suitable acknowledgments and references are provided. The detailed numerical data including matrices and functions for the identified models is provided in Annexure-I. The numerical data regarding the performance comparison metrics of each model is provided in Annexure-II.

2. System description

The residential HVAC system is installed at the Toronto Region and Conservation Authority Archetype Sustainable House (TRCA-ASH) in Vaughan, Ontario, Canada. Fig. 1(a) shows the front view of TRCA-ASH with In-Law Suite on the left, House-B in the middle and House-A on the right. House-A and House-B are semi-detached houses. The House-A is outfitted with the traditional HVAC equipment comprising of heat recovery ventilator (HRV), single-zone air handling unit (AHU) and air source heat pump (ASHP) typical of many Canadian households. The House-B comprises of more advanced HVAC equipment aimed at the futuristic housing projects such as net zero buildings. The HVAC system in House-B comprises of energy recovery ventilator (ERV), multi-zone AHU, ground source heat pump (GSHP) and radiant floor heating (RFH) system. The In-Law Suite receives its heating and cooling from the House-B HVAC system. In this paper, only the modeling of House-B HVAC system is discussed. The HVAC system of House-B modeled in this paper is shown in Fig. 1(b)–(e). The data acquisition (DAQ) system from National Instruments (NI) is shown in Fig. 1(f) which was used to capture the input-output data of the House-B HVAC system for modeling and validation. A simplified block diagram of the TRCA-ASH HVAC system is supplied in Fig. 2. A comprehensive system description can be found in the previous research on TRCA-ASH in [48–52]. The heating is supplied by the RFH system and the cooling is supplied by the AHU. The water is stored in the buffer tank (BT) to supply the hot and cold water to the RFH and AHU systems. The temperature of the BT water is maintained by the GSHP. In the winter, hot water is supplied by the GSHP and in the summer cold water is supplied by the GSHP to the BT. ERV transfers the energy from the outgoing stale air to the incoming fresh air.

3. Modeling

Each of the subsystem including ERV, AHU, BT, RFH and GSHP is modeled separately. The inputs and outputs of these models are shown in Fig. 3. All the systems have multiple inputs. ERV, AHU and RFH systems have multiple outputs whereas BT and GSHP systems have single output. The measurements are performed on all inputs and outputs of these multiple-input and single-output (MISO) and multiple-input and multiple-output (MIMO) systems. The temperature and flow rate measurements in all air and water loops were performed at an interval of 5 s and the data was stored in SQL database. The high resolution data captures the process dynamics very well but is not suitable for the modeling purpose as it results in large datasets resulting in increased time spent in training the models. The data was extracted from the database and median filtering was applied to remove the spiked noise in the measurements. The data was then down sampled to reduce the data resolution while keeping its ability to capture all the necessary process dynamics. This data was used to develop the gray-box models and black-box models of the system. Fig. 4 shows the data used for modeling and validation of each subsystem. The