Digital Recursive Filters for Building Thermal Modelling

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Abstract

The digital recursive filters where proposed as models of the thermal dynamics of the building. The developed wireless system of temperature sensors has been applied in collecting a large body of data. From physical consideration, the first-order recursive filters describe the thermal dynamics in the observed temperature range adequate. Evaluation of the filter parameters was performed using system identification. The proposed models are usable in electronic control systems for energy-saving heating management.

1. Introduction

On the one hand, a smart house should have an energy-efficient thermal control system, and on the other hand, the system should provide a comfortable room temperature. Therefore, in such a system, sophisticated algorithms are often used. For example, a fuzzy approach (from methods for expert systems), a neural network are offered [2, 3]. Most often, as a rule, various PID controllers are used as thermal controllers. In any case, the quality of management is largely determined by the adequacy of the model for the controlled system. The model that takes into account such building features, as the heat capacity, the thermal conductivity of walls would allow implementing effective energy saving strategies.

This paper presents the digital recursive filters as models for thermal dynamics of buildings. The theory of digital filters is one of the advanced areas of electronics [1], so the application of the filters allows using a diverse arsenal of methods for designing control systems. The structure of the filters is defined by physics of the heat transfer in the building. Parameters of the models are estimated by system identification using a large amount of experimental data.

2. The building under investigation

A three-story building of the engineering institute was chosen for data collection. Fig.1 gives the heating scheme of the building.

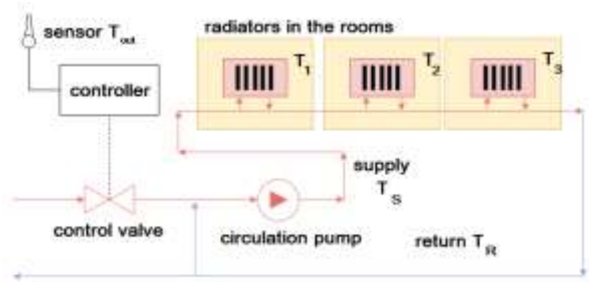

Fig.1. The building heating scheme

The supply water temperature from a district heat station is around 100°*C*. The electronic weather compensated temperature controller maintains temperature in range 40-60°*C* to the room radiators. The difference of the water pressures in the supply pipe and in the return pipe is held constant by the circulation pump. At a constant flux of the hot water the heat consumption of the building is determined by a difference of the supply temperature T_S and the return temperature T_R. That difference is $T_S - T_R < 5°C$. The temperature of the room radiators for calculations will be considered as average between the supply temperature and the return temperature.

3. Experimental data

To collect the experimental data a wireless sensor system has been developed. Each module of the system is made on the low-power system-on-chip (C1111, Texas Instruments, USA) [6]. The data from the temperature sensor is sent to the base station over 433 MHz channel. The Sub 1Ghz RF and the narrow band

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communication offer more than 2 km coverage for the system. The user web interface of the base station provides an easy way to control the system in operative (Fig.2).

Fig.2. The user web interface of the base station

The data from the temperature sensors was collected over 5 months in 20-minute increments. Database MySQL is used to store data. That large amount of the date assures reliability of estimates for parameters.

Fig.3 shows the movement of the temperatures with time.

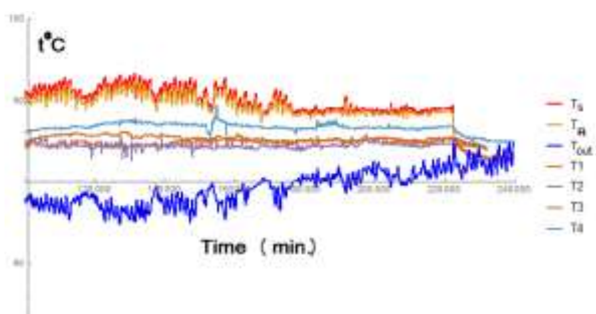

Fig.3. The experimental data obtained in January-April 2018

All temperature curves have a daily period associated with fluctuations in the outdoor air temperature. The electronic weather compensated temperature controller maintain an inverse proportion between the outdoor air temperature and the water temperature in the supply pipe.

4. The theoretical basis of the model

The room temperatures are determined by the heat fluxes and the heat capacitance of the room. The equations will neglect the heat fluxes between the rooms. Indirect that processes modify the estimates of the room capacitance. Within the temperature range the linear differential equations are reasonably adequate. Based on above assumptions, energy balance governing equations for every room can be written as:

$$C\frac{dT_i}{dt} = k_h(T_h - T_i) - k_{out}(T_i - T_{out})$$

where T_h is temperature of the room, C is thermal capacitance of the room, T_h is temperature of the radiators, T_{out} is the outdoor air temperature, k_h and k_{out} are the corresponding heat transfer coefficients.

The coefficients k_h and k_{out} depend on many factors: radiation, convection, thermal conductivity of materials and theoretically it is very difficult to calculate them. It is also difficult to calculate the heat capacity C.

This differential equation can be associated with the difference equation. In the end, the difference equation corresponds to the recursive digital filter:

$$T_i(t) = AT_i(t-1) + B_1T_h(t) + B_2T_{out}(t)$$

where A, B_1, B_2 are expressed in terms C, k_h, k_{out}. Time is measured in units of sampling, in this work this unit is 20 minutes.

Thus, information about the thermodynamic parameters of the building goes into the coefficients of the digital filters. The values of these coefficients will be obtained by standard methods of system identification.

Using standard theoretical methods of working with digital filters, in particular, z-transformation [5], we can obtain the most suitable algorithms for the temperature control system. For example, a selection of proportional, integral, and derivative terms for PID controller is difficult task [4], as a rule, they are chosen experimentally. Having a digital model, we can calculate these coefficients theoretically; in addition, it is possible, for example, to analyze the controller's operation for stability. Using the z-transformation, it is possible to design a reverse filter, on the basis of which to build a sequence of input radiator temperatures for a given outdoor air temperature forecast, which will ensure the desired dynamics of the room temperature.

5. System identification

To estimate the parameters of the digital filters we used System Identification Toolbox from the MATLAB. The parameters have been estimated using subspace method. Subspace identification methods aim at directly estimating the system parameters in a state-space model structure from noisy input–output data. That method indicated in short as 4SID, i.e., Subspace State-Space System Identification [8,9].

The result of the identification for a large room is the equation:

$$T_i(t) = 0.98 \cdot T_i(t-1) + 0.013 \cdot T_h(t) + 0.008 \cdot T_{out}(t)$$

Fig.4 shows the fitness of the model to the experimental data. The unit of time in the figures and in the filters corresponds to 20 minutes.

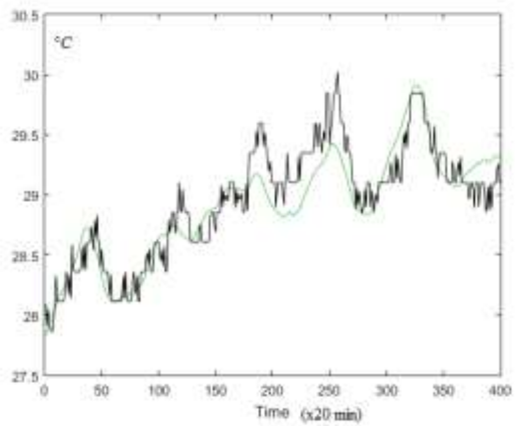

Fig.4. Measured and simulated model output for a large room (the green curve is model, the black curve is experimental data)

Next equation is the digital recursive filter for small classroom:

$$T_i(t) = 0.94 \cdot T_i(t-1) + 0.025 \cdot T_h(t) + 0.013 \cdot T_{out}(t)$$

Fig.4 and Fig.5 illustrates the action of a noise. In small classroom activities of people make noise and experimental data deviate widely from model curve. The air temperature in the big room is determined by T_h and T_{out} considerably more. The coefficient at $T_i(t-1)$ indicate the thermal capacitance of the room, and other coefficients relate to power of the radiators and heat loss of the rooms.

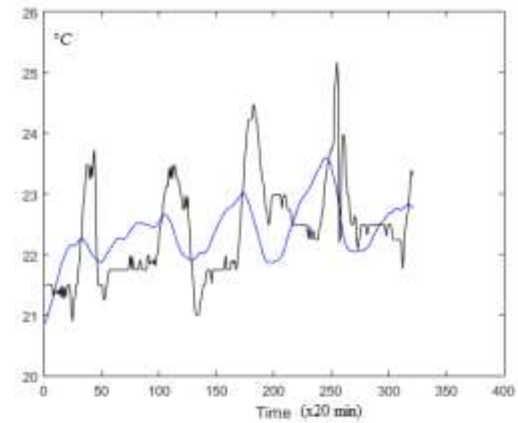

Fig.5. Measured and simulated model output for a small classroom (the blue curve is model, the black curve is experimental data)

The described procedure is adaptable to the building as a whole. In this case the output is $Y = T_S - T_R$, the difference is proportional to the heat consumption of building. The input is vector (T_S, T_{out}). System identification gives the following equation:

$$Y(t) = 0.55 \cdot Y(t-1) + 0.03 \cdot T_S(t) - 0.005 \cdot T_{out}(t)$$

It is apparent that the heat consumption is greater, the smaller T_{out}, because of this the coefficient at T_{out} is negative.

Fig.6 shows that the model fits the experimental data reasonably well.

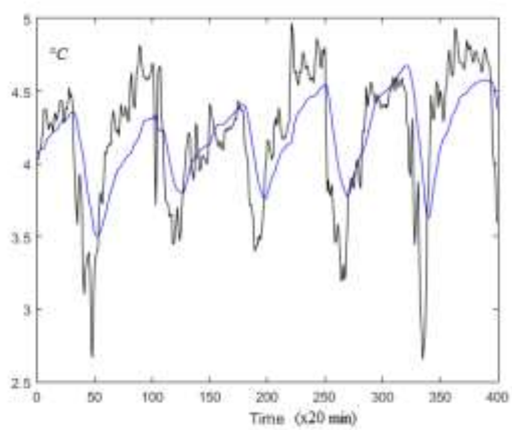

Fig.6. Measured and simulated model output for the building as a whole (the blue curve is model, the black curve is experimental data)

This model can be used to for analysis of heat consumption under different scenarios for heat management.

6. Conclusion

A model is necessary to predict a change of an object with time and to manage the object. On the one hand, digital filters are native to electronics and implemented by electronic devices very simple, and on the other hand, the digital filters simulate the temperature dynamics acceptable. We propose to take in account peculiarities of the concrete building rather than to complicate model.

By applying the proposed models, sophisticated management strategies can be realized. For example, the heating system can be switched off at night and activated just in time to warm the rooms to a comfortable temperature until the arrival of employees in the morning.

Future work will assess the reusability of the modeling procedure by applying it on several types of buildings. The database of developed system stores data on wind and solar radiation, but accounting for this data in the models is in the future.

7. References

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