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MODELLING AND MODEL-BASED CONTROL OF AN HVAC SYSTEM

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Abstract

An HVAC system contains heating, ventilation and air conditioning equipment used in office or industrial buildings. The goal of this research is to design a controller for the process of cooling an office building that is made up of three rooms. The desired room temperature can be achieved by controlling the fans making up the fan coil units and the cooling medium's temperature. By these means the building connected to the electrical grid becomes a smart office. The used building model includes several dynamically changing interior and exterior heat sources affecting the inner climate, which introduces a level of uncertain prediction into the system. We have determined the controller's performance by the rate of deviation from the expected temperature, the consumed electrical energy and the generated noise. The controller was created in Matlab Simulink with the possibility of migration to a Siemens PLC.

Keywords: *modelling, temperature, controller, cooling, prediction.*

1. Introduction

This research is based on the industrial challenge organized under the MED'18: The 26th Mediterranean Conference on Control and Automation, in which Kardos T. took part as member of the SapiEngineering team. The goal was to design a controller for the given cooling system, which ultimately had to be implemented on a Siemens PLC. The received system's model was created in Matlab Simulink, for which we will describe only the main parts. For further details see [1].

The system's controllable inputs are the cooling medium's temperature (T_s) and the fan coil units' signals (FS_1, FS_2 and FS_3). The room temperature is primarily influenced by the cooling air from the fan coils, but other effects are modelled as well: outdoor air temperature, solar irradiance and heat disturbances, such as the presence of people or operation of machines. These factors are modelled using predictions with a degree of uncertainty. **Figure 1.** shows the used system's schematic.

Another existing method for describing a building is to create models based on linear parameters obtained from BMS data [2]. BRCM modelling is used to model a similar building in [3]. A more complex system containing heating, cooling and ventilation is discussed in [4].

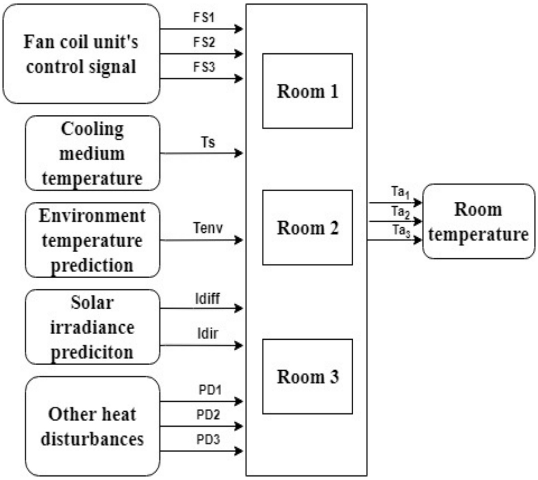

Figure 1. *System's schematic*

2. Controlled system

2.1. Building model

The modelled office building consists of three south-facing rooms, each one containing one fan coil unit. We can describe the building dynamics using a state-space model shown by (1).

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned}, \tag{1}$$

where the state vector x includes the T_a air, and T_{wall} wall temperatures of the three rooms.

$$x = \begin{bmatrix} T_{a,1} & T_{a,2} & T_{a,3} & T_{wall,1} & T_{wall,2} & T_{wall,3} \end{bmatrix}^T \tag{2}$$

The u input vector is built up of the T_{env} environmental air temperature, I_{dir} direct solar irradiance, Idiff diffuse solar irradiance, P_{FCU} actuator thermal powers, and P_D other heat disturbances.

$$u = \begin{bmatrix} T_{env} & I_{dir} & I_{diff} & P_{FCU,1} & P_{FCU,2} & P_{FCU,3} & P_{D,1} & P_{D,2} & P_{D,3} \end{bmatrix}^T \tag{3}$$

The T_{env}, I_{dir} and I_{diff} external weather conditions are equal to the sum of the prediction values and prediction errors modelled with Gaussian distribution. The P_D disturbance heat fluxes can also be described using Gaussian distribution with the following equation:

$$P_{D,i} = \begin{cases} k_i + w_{D,i} & ha \quad 8:00 \le h \le 18:00 \\ w_{D,i} & otherwise \end{cases} \tag{4}$$

where k_i represents a greater heat flux that appears during fixed working hours, defined separately for each room in equation (5). A similar approach was studied in **[5]**, where the inner temperature control is a function of people's presence in the room.

$$k_i = \begin{cases} 100 & if \quad i = 1 \\ 120 & if \quad i = 2 \\ 150 & if \quad i = 3 \end{cases} \tag{5}$$

The y output vector consists of the inner room temperatures:

$$y = [T_{a,1} \quad T_{a,2} \quad T_{a,3}]^T \tag{6}$$

2.2. Cooling system

The fan coil units used in the cooling system are the most commonly installed temperature regulators in office buildings. Its higher performance when compared to classical solutions makes it a better choice for heating or cooling purposes.

During cooling a regulated cooling medium is circulated through the fan coil unit, while its fans are used to spread the cooled air in the room **[6]**. The electric power of the modelled fan is 50 W when turned on, and 0 when the fan is off. The cooling medium's possible temperature values are limited to: T_s є [7,11].

The model takes into consideration the heat loss appearing in the pipework as well.

2.3. Predictions

Different forecast data was available for the controller's development.

This includes the environmental temperature, the direct and the diffuse solar irradiance, which are all part of the system's inputs. Every hour a new forecast is available, reaching a total of 24 hourly sampled values.

Additionally, the temperature set point also has a 24 hour prediction, constrained within the lower and upper temperature bounds following this rule:

$$\begin{gathered} L_b \le SP_i \le U_b \\ L_b = \begin{cases} 24 & if \quad 8:00 \le h \le 18:00 \\ 0 & otherwise \end{cases} \\ U_b = \begin{cases} 24 & if \quad 8:00 \le h \le 18:00 \\ 100 & otherwise \end{cases} \end{gathered} \tag{7}$$

As equation (7) shows, during working hours the temperature reference is constantly set to 24 degrees. Outside this interval the set point can have any value since in this period no cooling medium is circulated through the system, and the penalization cost doesn't include the temperature deviation either.

The electricity price also has a 24 hour prediction vector that changes every 15 minutes (c_{el}).

2.4. Cost functions

The system's performance is measured with the cost of operation in Euros, described by the following sum:

$$J = J_1 + J_2 + J_3 , \tag{8}$$

J_1 is the cost of consumed electrical energy:

$$J_1 = \int_{\tau=0}^{T_{sim}} \frac{c_{el}(\tau)}{3.6 \cdot 10^6} \left(P_{el}^{P}(\tau) + P_{el}^{HP}(\tau) + \sum_{i=1}^{3} P_{FCU,i}(\tau) \right) d\tau , \tag{9}$$

where

c_{el} [EUR/kWh]] is the cost of electricity,

T_{sim} [s] ais the simulation time,

P_{el} [W] is the consumed electric power.

J_2 is the cost of deviating from the temperature reference:

$$J_2 = \int_{\tau=0}^{T_{sim}} \varphi(t) \frac{c_{el}(\tau)}{3.6 \cdot 10^6} \sum_{i=1}^{3} Q_i (T_{a,i}(\tau) - SP_i(\tau))^2 d\tau \quad (10)$$

where

Q_i is the weight coefficient for penalization of the temperature deviation, and,

$\varphi(t)$ sets the tracking error to be considered only during working hours.

$$\varphi(t) = \begin{cases} 1 & \text{if} \quad 8:00 \le h \le 18:00 \\ 0 & \text{otherwise} \end{cases} \quad (11)$$

J_3 cost is used to measure the acoustic discomfort in the rooms:

$$J_3 = c_{ON} \sum_{j=0}^{N_{sim}} \sum_{i=1}^{3} \delta_i(j) \quad (12)$$

$$\delta_i(j) = \begin{cases} 1 & \text{if} \quad FS_i(j) = on; FS_i(j-1) = off \\ 0 & \text{otherwise} \end{cases} \quad (13)$$

where

c_{ON} is the cost of turning the fan coils on,

δ_i is the fan's on or off state,

j denotes the 1 minute discrete periods,

N_{sim} is the total number of time instants in one simulation.

3. Designed controller

Several methods exist for the control of similar systems. Fuzzy neural networks and MPC containing genetic algorithms are compared in **[7]**. PID and robust PID are presented in **[8]** and **[9]**. A Fuzzy rule-based controller is designed with PID properties in **[10]**.

The controller designed by us is made up of two parts: the first is the calculation of the control signal sent to the fan coil units, and the second is the algorithm regulating the cooling medium temperature. **Figure 2.** shows the control loop's schematic.

Because the fan coils could be either in turned on or off state, we determined their control signal using a PWM generator. Its pulse width was calculated with a discrete PI controller based on the difference between the given temperature set point and the measured indoor temperature.

To calculate the controller's proportional parameter (K_p) we used the prediction values of the direct solar irradiance, because these had the biggest effect on the room temperature. After several simulations we decided to take into consideration only the next 4 hour values out of the existing 24 hour vector:

$$K_p = \frac{(I_{dir}(k|k) + I_{dir}(k+1|k) + I_{dir}(k+2|k)}{100} + \frac{+I_{dir}(k+3|k))}{100} + 5 \quad (14)$$

The integrative parameter of the controller is directly influenced by the environment temperature downscaled with 100:

$$K_i = \frac{T_{ext}}{100} + 5 \quad (15)$$

For the final control signal we used the other predictions as well. As a result, the PWM's pulse

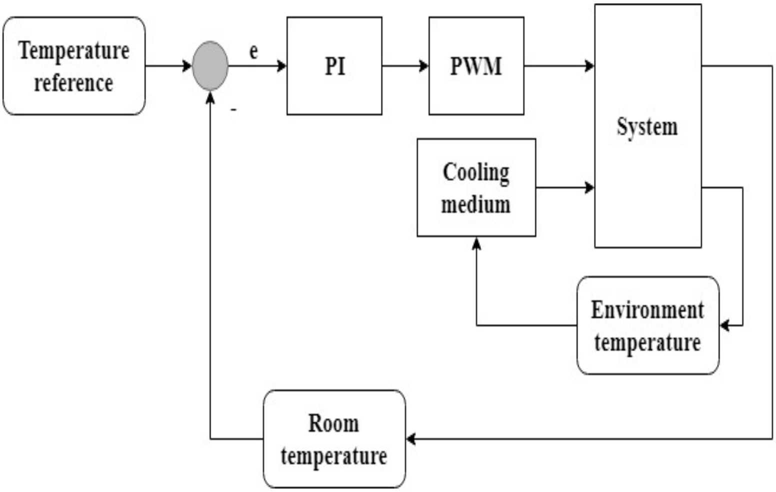

Figure 2. *Schematic of the control loop*

width is also determined by the electricity price prediction vector, from which only the following first hour's cost is of importance. Thus, a greater price leads to a smaller pulse width and shorter functioning time in the end.

Besides the cases set by the PWM, the fan's state is also influenced by the diffuse solar irradiance's and the environment temperature's prediction vector. Similarly to the direct solar irradiance vector, only the values from the first 4 hours were applied. These factors affect the output only when a certain limit is passed and a high control error occurs.

When regulating the cooling medium's temperature we aimed for energy efficiency, so high performance cooling was applied only when needed. Controlling was done using the actual environment temperature, with regard to the allowed temperature boundaries (7-11 degrees). Hence, if the outside temperature dropped below 20 degrees, the cooling medium was set to 11 degrees, otherwise a 7 degree cooling medium was circulated.

3. Results

We ran a simulation of the system control for 3 days with the reference temperature set to 24 degrees Celsius.

In the followings, for easier understanding we will only show the first day's results, even though we simulated 3 days. On **Figure 3.** we can see the temperature's change in time in the three rooms. **Figure 4.** shows the plot of the controlled cooling medium.

The environment temperature's change is shown in the first graphic of **Figure 5.**, while the second and third graphics show the direct and diffuse solar irradiance values.

We can notice that the rooms' temperature has a ±0.6 degrees Celsius deviation from the set temperature. The temperature shows a greater dynamic during daytime, when outside temperature is higher and the building is affected by solar irradiance too, which in turn results in an increased inside temperature. During night, the temperature deviation falls to ±0.1 degrees.

Figure 6. shows the other heat disturbances affecting room 1. These high rates also have a great impact on the temperature's fluctuation.

On **Figure 7.** we can examine the control signals sent to the fan coil units' fans. One can easily distinguish the moments when the fans are in turned on or off state. The three control signals

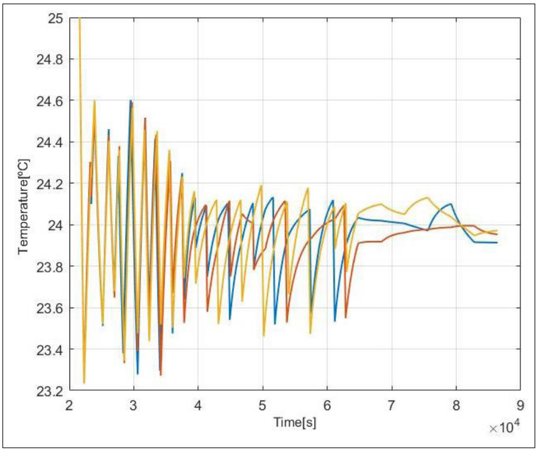

Figure 3. *Temperature in the three rooms*

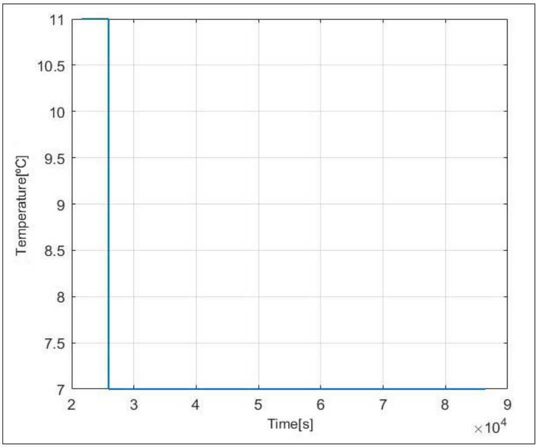

Figure 4. *Cooling medium's temperature*

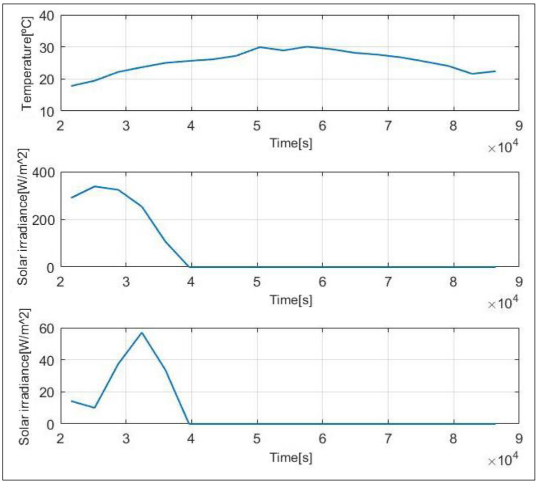

Figure 5. *Environment temperature, direct and diffuse solar irradiance*

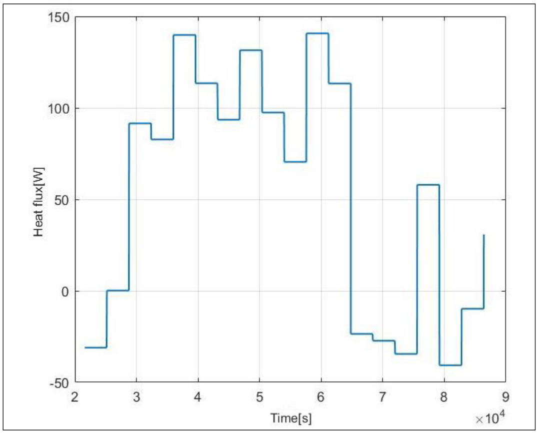

Figure 6. *Other heat disturbances in room 1*

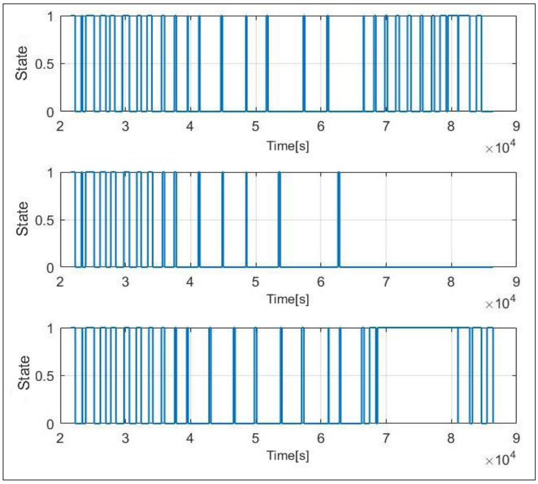

Figure 7. *Fan coil units' control signals*

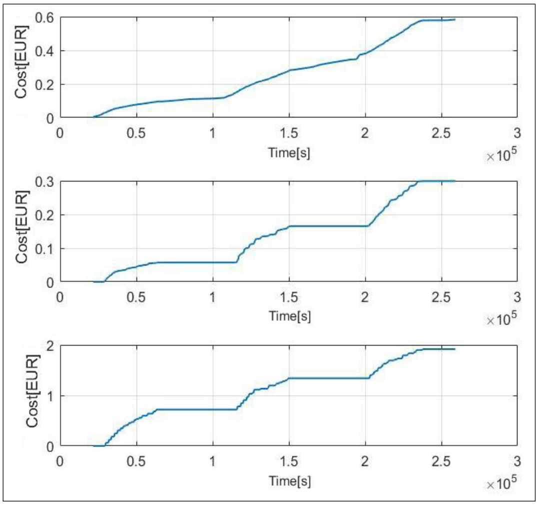

Figure 8. *Cost of consumed electrical energy, deviation from temperature reference and acoustic discomfort*

have a similar dynamic, although the second room's values differ on a larger scale. This mainly results from the heat disturbances' variations and random nature.

Our measured control cost after a three day simulation was 2.799 EUR, with the applied electricity price fluctuating between 0.01 – 0.09 EUR/kWh. **Figure 8.** shows the three costs' change over time. Based on the results, the largest cost (1.91 EUR) was due to the acoustic discomfort produced during the fans' turned on state. The cost of the used electrical energy followed with 0.58 EUR. The smallest cost (0.29 EUR) resulted from the actual temperature's deviation from the temperature reference, which shows the controller's optimal behavior.

4. Conclusions

In this paper we presented a control algorithm developed for a modelled office building's cooling system, during which some external factors affecting the office's temperature were also taken into consideration. Our simulation results prove that the controller successfully follows the set reference with a small, but acceptable deviation. Furthermore, it can be deducted that the direct solar irradiance and inner heat disturbances have the greatest effect on the indoor temperature.

In conclusion, the developed controller represents a cost-effective solution to the control of a system containing dynamic inputs. With certain changes this controller can be used for heating purposes as well.

Acknowledgements

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