DEVELOPMENT OF A HOME TEMPERATURE CONTROL UNIT BASED ON A MODEL PREDICTIVE CONTROL STRATEGY

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Abstract: The paper presents the development of a home temperature control unit that aimed to replace standard residential building temperature control units with one which has superior performance and improves the comfort for occupants. The new developed system integrates a model predictive control strategy and building model online identification algorithms that assure a large applicability for different buildings. The implementation of the control unit is performed using the Discovery development board. For testing the control unit a Hardware in the loop simulation experiment is developed using dSpace platform. The obtained results showed that the proposed systems have better results from energy efficiency point of view.

Keywords: *temperature control unit, rapid control prototyping, MPC control strategy.*

I. INTRODUCTION

The buildings energy consumption at global scale reach values around 40% of the total global energy consumption [1]. This value is increasing constantly due to different social and economic factors; examples in this way are the developing countries which are characterized by a constantly increasing energy use booth in industry and residential areas [2]. This evolution cause global concerning related to the limited amount of natural resources and the destructive effect to the surrounding environment which leads to unwanted climate changes.

In this context optimization of the energy consumption in buildings can prove to be an important factor in decreasing the energy consumption at global level [3]. The current paper focuses its research on increasing the energy efficiency in residential building. In this field the optimization can be realized in different ways. One approach is to upgrade the building structure or to replace the old appliances with new ones which are more energy efficient [4]. Another approach, less invasive and with less investments than the previous one, is the implementation of smart automation systems which control more efficient the indoor environment. Based on the user preferences, such systems can control different building parameters such as heating, air conditioning, lighting etc. in an efficient manner with increased comfort for the occupants [5]. Due to the high percentage of energy consumption used by the heating systems (around 68 % in Europe [6]) noticeable results in reducing the energy use can be obtained by improving the heating process of the houses [7].

The efficiency increase in energy consumption is obtained by implementing more advanced control strategies. In the literature different approaches can be found [6]. One promising approach is the use of model predictive control (MPC) and the model of the house for optimization purposes [8]. Compared with other control strategies, MPC uses a mathematical model of the controlled process to predict system behavior and compute the optimal control signal [9].

One drawback in implementing this type of control strategies was the necessity of high computation power from the hardware board. The development in the electronics hardware in the last years facilitates the emergence of new development boards with good cost/performance ratio. In this paper the possibility of using such a development board for creating a new temperature unit control which implements an MPC control strategy is analyzed. The aim is to develop a cost effective new system/product that can replace the standard on-off thermostats which currently is used largely in the residential buildings. For testing the obtained system a HIL simulation experiment is developed using the dSpace simulation platform. The algorithms and the obtained results are presented in the next sections.

II. MPC CONTROL ALGHORITHM

The developed system implements a model predictive control algorithm for regulating the temperature variation in the building. The control algorithm was presented by the authors in [7]. The algorithm identifies online the model of the building during operation and uses it to predict the process behavior and to compute the control signal (figure 1).

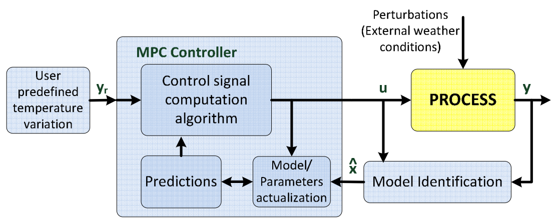

Figure 1. Control system – block scheme

The outputs of the control algorithm are limited to 0 and

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1 due to the specificity of the usual heating systems used in residential buildings. This approach aims to facilitate easily replacement of the standard On-Off thermostats.

In order to implement the MPC control algorithm a model of the controlled process is needed. In this work the process is considered as a Single Input Single Output (SISO) system. The identification algorithm uses an ARX (auto regressive with exogenous terms) model (eq. 1) to describe the process dynamics. The model is identified online based on the command signal from the control unit and the room ambient temperature variation.

$$y(t) + a_1 y(t-1) + \cdots + a_{na} y(t-na) = b_1 u(t-nk) + \cdots + b_{nb} u(t-nk-nb+1) \qquad (1)$$

The model is completely defined if the terms *na* (number of stored input signals), *nb* (number of stored output signals) and *nk* (the system dead time parameter) are known [10].

The control algorithm uses the identified model to simulate future behavior of the process over a finite horizon *N*, for a set of possible control sequences (eq. 2) and then to choose the control sequence which generates the best response. This approach is different comparative with usual MPC algorithms which use an optimization algorithm.

$$u(.) = \{u(t), u(t+1), \ldots, u(t+N)\} \qquad (2)$$

If all possible command sequences were to be calculated, the control system would need a very long computational time. As a consequence the number of the sequences must be reduced. In [11] a set of four control sequences is proposed as a solution to find a quasi-optimal control signal. The sequences are:

$$\begin{aligned} u_1 &= \{u_{min}, u_{min}, \ldots, u_{min}\} \\ u_2 &= \{u_{max}, u_{min}, \ldots, u_{min}\} \\ u_3 &= \{u_{min}, u_{max}, \ldots, u_{max}\} \\ u_4 &= \{u_{max}, u_{max}, \ldots, u_{max}\} \end{aligned} \qquad (3)$$

where u_{min} and u_{max} are the two states of controller output.

Based on these commands sequences a set of outputs sequences are calculated $y_i(t)\{i = 1..4\}$. The control signal is then obtained using the extreme values y_{max0}, y_{max1}, y_{min0}, y_{max1} from the output prediction sequences.

The following rules are used (the presented rules apply for processes with positive sign) [11]:

1. Case 1: if $y_{max0}<y_r$ and $y_{max1}>y_r$ then using a linear interpolation the *aux* parameter is calculated

$$aux = \frac{1}{y_{max1} - y_{max0}} - \frac{y_{max0}}{y_{max1} - y_{max0}} \qquad (4)$$

if $aux>0.5$ then $u(t)=1$ else $u(t)=0$.

2. Case 2: if $y_{min0}<y_r$ and $y_{min1}>y_r$ then using a linear interpolation the *aux* parameter is calculated

$$aux = \frac{1}{y_{min1} - y_{min0}} - \frac{y_{min0}}{y_{min1} - y_{min0}} \qquad (5)$$

if $aux>0.5$ then $u(t)=1$ else $u(t)=0$.

3. Case 3: if $y_{max0}>y_r$ then $u(t)=0$.
4. Case 4: if $y_{max1}<y_r$ then $u(t)=1$.

III. HARDWARE IMPLEMENTATION

The controller is implemented using the development board Discovery STM32F4. The board is built around the 32 bit ARM Cortex-M4F microcontroller that runs at 168 MHz and integrates a vast number of I/O and communication ports that facilitate the connection with the sensor and actuation systems.

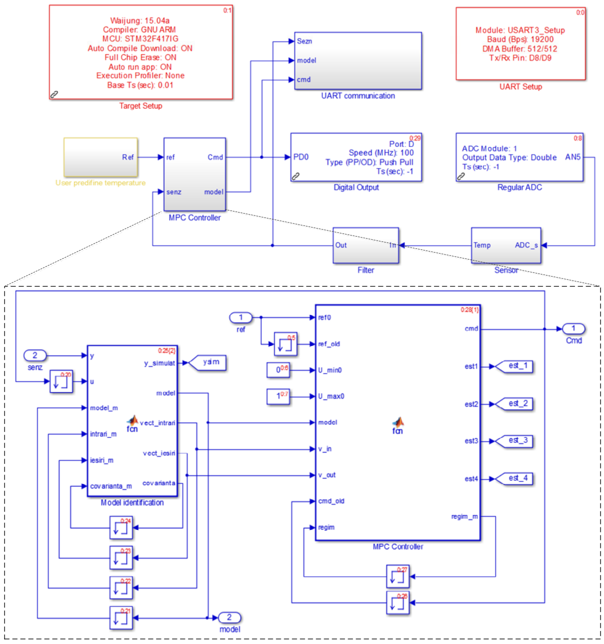

Figure 2. MPC Simulink Model

An advantage of using the Discovery development board is the possibility to implement directly the control algorithm developed in MATLAB/Simulink via automatic code generation. Besides the control modules the model includes also Simulink blocks for the board peripherals which are provided by the Waijung library.

The obtained Simulink model that is used for implementing the MPC control algorithm on the Discovery board is presented in figure 2. The data from the temperature sensor is collected using ADC 1 port and the control signal is transmitted to the heating system through I/O PD0 port. The main control parameters (control signal, sensor data, identified model, estimation sequences) are also transmitted for monitoring purposes using the UART board interface.

The Discovery platform enables setting a different sampling time for the blocks in Simulink model as multiple of a sampling basis of 0.01 [s]. For the MPC controller the sampling time is 10 [s].

IV. EXPERIMENTAL RESULTS

In order to test the control system performance a hardware in the loop simulation (HIL) was developed. HIL simulations enable development of complex experiments that combine real components with virtual components defined by mathematical models [12]. Usually, for HIL simulations, the real component is the control unit and the virtual component is the process which is controlled. The embedded controller is connected to the building model through dedicated interfaces on the simulation platform.

The developed experiment set up is schematically presented in figure 13. The control process runs in real time on dSpace 1104 simulation board and the developed control system (Discovery platform) is connected to the process through dSpace interface board.

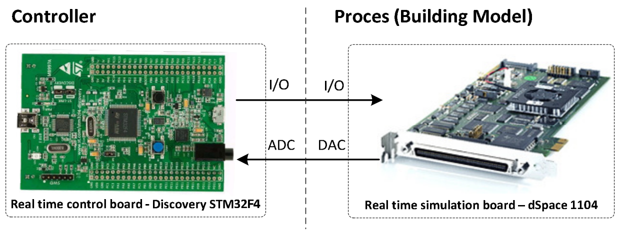

Figure. 3. Hardware in the loop simulation

The controlled process is materialized by a house with four rooms (figure 4). The development of the analytical model of the building was presented by the authors in [13]. The model includes: rooms models, heating system model, ventilation system model and the influence of the external environment parameters to the building thermodynamic (air temperature, solar radiation and soil temperature). The building model that is loaded on dSpace platform contain, beside the analytical model, connectors block that facilitate collection of data (rooms temperature) and to control the heating system in the building through physical interface ports (DAC, I/O). The simulation runs in real time, the sampling time is 0.1 [s]. For solving the equations that define the building model the *ode14 (extrapolation)* fixed step solver from Matlab/Simulink was used.

The external environment parameters that are used during simulations were measured in Cluj-Napoca city. The parameters were measured in January hourly. They are: outdoor air/soil temperatures (figure 5) and the solar radiation (figure 6). The soil temperature during this month was about -2 [ºC].

The developed experiments tested the MPC control system response for a period of 14 hours (from 4 AM to 6 PM). The initial temperatures inside building rooms were: 21 [ºC] in *room1*, 20.5 [ºC] in *room4*, 20 [ºC] in *room2* and 19.5[ºC] in *room3*.

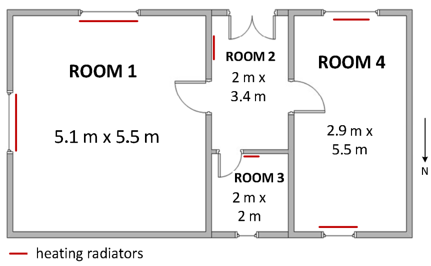

Figure. 4. Building Sketch[13]

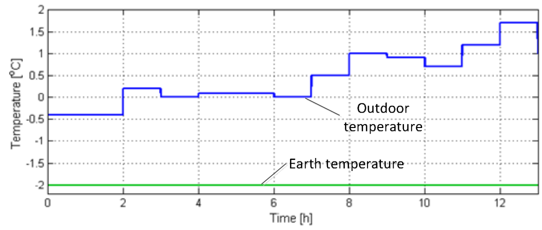

Figure. 5. External environment – temperature variation

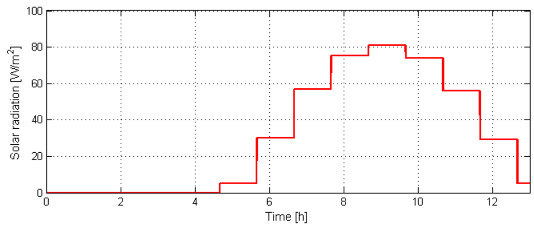

Figure. 6. External environment – Solar radiation

The obtained results are presented in figure 7. The MPC controller response was compared with a standard On/Off controller which was implemented on the same development board. In booth experiments the building model and the simulation conditions were the same. The reference value was the temperature in *room1*which wary from 20 to 21[ºC] in different periods of time.

The implemented on/off controller has a sampling time of 5 [s]and is characterized by a dead zone of 0.25 [ºC].

The prediction horizon is set to 120 steps, that means for a 10 [s] sampling time the predictions evaluate the system behavior for 20 minutes in the future. The possible values for the outputs are u_{min}=0 and u_{max}=1. The ARX model has the parameters *na = 4 , nb = 3 and nk=2.*

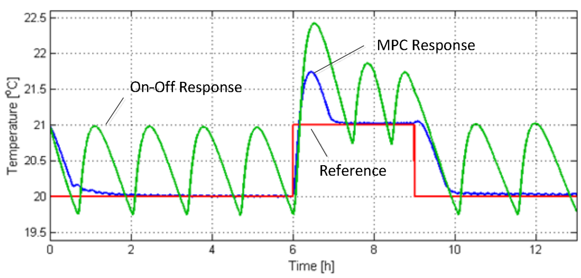

Figure 7. System response using the On-Off and MPC Controller

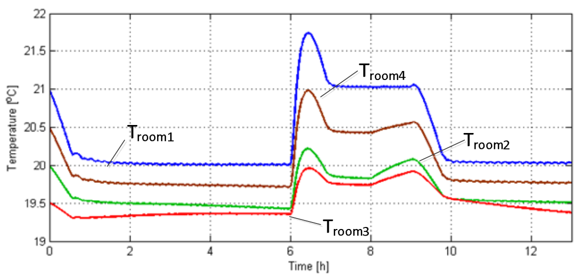

Figure 8. Temperature variation in building rooms

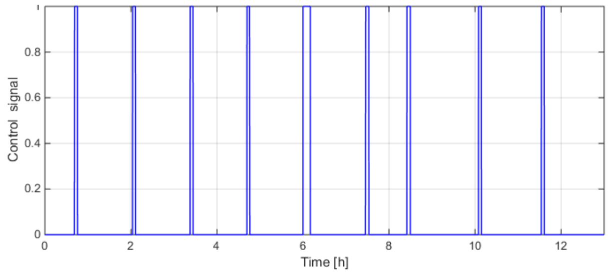

Figure 9. Control signal- On-Off Controller

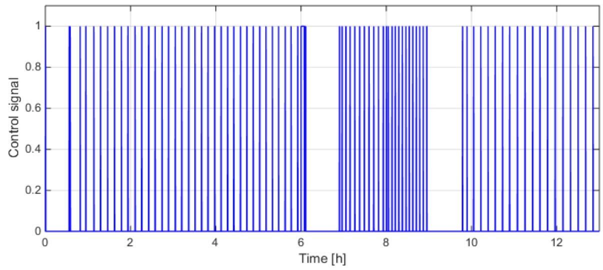

Figure 10. Control signal- MPC Controller

It can be observed that the MPC response exceeds the performance behavior of the on-off controller. The mean square temperature error inside *room1* for MPC control system is $e_{mpc}=0.079$ and for on-off control system is $e_{on\_off}=0.4528$. The errors variation during HIL simulations is presented in figure 11.

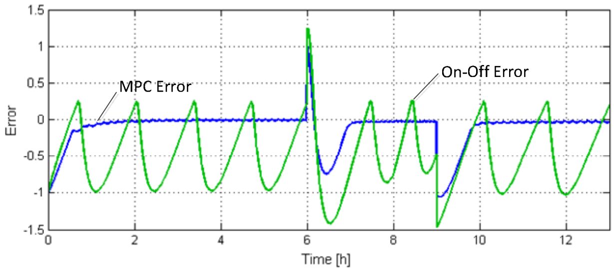

Figure 11. Error for On-Off and MPC Controller

The control signals for the two controllers are presented in figure 9 and 10. The energy consumptions for heating in the case of MPC control system was less with 12% than the On/Off Controller. It can be observed that a possible drawback of the new proposed control system is the increase frequency in commutation from on to off of the heating system. This negative aspect can be overcome by imposing a minimum transition time to the controller, resulting in less commutation events and with possible decrease in overall performance.

V. CONCLUSION

The paper presents the development of a temperature control unit that aimed to replace the standard thermostat in residential buildings. The proposed control unit integrates algorithms for identifying the process model and a set of control sequences to estimate the future behavior of the system in order to compute the quasi-optimal control signal at the actual moment.

The experimental results showed an improvement in system behavior comparing with standard on-off thermocouple. The improvement can be observed booth in occupants comfort, by maintain a closer temperature to the imposed reference temperature in the room, and by reducing the energy used by the heating system.

The results showed that the proposed system can offer a better alternative to the system that are today used for controlling the temperatures inside the residential buildings.

In the future, starting from the presented results, work will focus on: testing the developed control module on a real building and study of other sets of control rules and sequences for the control algorithm.

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