# Hybrid Predictive Control System of Microclimate and Energy Consumption

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***Abstract*— The paper describes the system of a building microclimate and its energy consumption control. It covers both continuous (heat exchangers, radiators, convectors) and discrete (thermostats, fans, pumps) elements operating on the on/off principle. Such systems are described through mixed logical-dynamical models. To manage the system, an approach is proposed that allows integration of traditional climate control equipment and the latest systems based on predictive controllers. Various ways of hybrid predictive control implementation are considered. The results of the simulation confirm effectiveness of the proposed approach for microclimate control and energy consumption of buildings.**

***Keywords*— *microclimate; mixed logical-dynamical system; hybrid predictive control; MATLAB***

## I. Introduction

Modern urban residents spend more than 80% of their lives in closed premises. It has been proved that the microclimate of the premises significantly affects the physical and emotional state of people, as well as their working capacity [1]. Therefore, maintenance of the microclimate parameters, defined by the well-known sanitary norms which are comfortable for people's living, is the main task of the climatic equipment installed in the buildings. On the other hand, the need for energy saving and reducing utility payments necessitates minimizing the cost of energy resources to maintain the microclimate. These, often contradictory requirements, must be met by the Energy and Comfort Management System (ECMS) of buildings, including HVAC (Heating, Ventilation, Air Conditioning).

Traditionally, heaters, fans, “warm floor” systems and suchlike, operating on the on/off principle, as well as various control systems based on two-position, three-position and PID-controllers are used to control the microclimate of the premises. At present, in the scientific press, optimal and adaptive control systems, model predictive control (MPC) systems, as well as systems based on fuzzy logic, neurocontrollers and some others are widely advertised for buildings’ climate and energy consumption control [2]. The greatest number of publications falls on the systems using the MPC approach. These systems allow better management of buildings’ microclimate, with respect to the limitations, and at a minimum of energy costs. Such systems are now being actively implemented in practice [3]. However, traditional HVAC equipment is still going to be used for a long time, particularly, jointly, with the latest climate systems.

In general, the microclimate and energy consumption control system of a modern building includes both continuous (heat exchangers, radiators, convectors) and discrete (thermostats, fans, pumps) elements operating on the on/off principle. In addition, the microclimate of buildings can be influenced by various internal or external events related to people's living functions, equipment operation and other factors. From the point of view of the mathematical description, the modern building is a continuous-discrete or hybrid dynamical system consisting of interacting elements of a various nature whose behavior is described by both continuous and discrete processes.

In the scientific press, there are as yet few papers devoted to the task of controlling microclimate and energy consumption of buildings, considered as hybrid dynamic systems, while applying the MPC approach. The existing papers [4], [5] are mainly connected with the use of non-traditional energy sources and do not take into account the Russian specificity caused by the influence of special climatic conditions and the peculiarities of the domestic engineering systems of buildings.

## II. System Modeling

To implement modern methods of buildings’ microclimate and energy consumption control, such as optimal and adaptive control laws, it is necessary to have models of control objects. A large number of publications are devoted to creating mathematical and computer models of the buildings microclimate [6], [7]. For the purposes of management, however, only dynamic models with lumped parameters are so far suitable. The use of mathematical models with distributed parameters is currently not justified because of their high computational complexity.

Most of the developed microclimate models are non-linear and non-stationary. And that’s where the advantage of the MPC approach comes to the forefront: since it implements the control law through the system’s state feedback, and the control is considered and implemented within a very short period of time, it is sufficient to use only approximate linear models for the control synthesis. Therefore, in what follows, we will consider linear stationary models in the form of state-space representation, with discrete time, obtained from more

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complex non-linear and non-stationary models. Such models can be represented as follows:

$$x(k+1) = \mathrm{A}x(k) + \mathrm{B}u(k) + \mathrm{G}w(k), \tag{1}$$

$$y(k) = \mathrm{C}x(k) + \mathrm{D}u(k), \tag{2}$$

where $x(k)$ is a vector of state variables, $u(k)$ is a control vector, $w(k)$ is a vector of controlled disturbances, $y(k)$ is a vector of output (controlled) variables. The vectors of control and output variables are constrained

$$u(k)_{\min} \leq u(k) \leq u(k)_{\max}, \tag{3}$$

$$y(k)_{\min} \leq y(k) \leq y(k)_{\max}. \tag{4}$$

As it was mentioned earlier, various internal or external events can affect the microclimate of buildings. Some of them can be pre-programmed in advance, while others can arise absolutely casually. For example, in order to save electricity consumption, it is possible to periodically shut down the circulation pumps of the public and administrative buildings heating system. This event can be assigned a binary logical variable $\delta_1 \in \{0, 1\}$. If $\delta_1 = 0$, this corresponds to the 'on' state of the pump. In this case, the system model can be described through equations (1) and (2). If $\delta_1 = 1$, this corresponds to the 'off' state of the pump. In this case, in the model of the system (1), (2) instead of matrix B, a new matrix $\mathrm{B}_1$ will be used.

In general case, each event can be assigned a logical variable $\delta_s$, $s = 1,\ldots, S$, and each logical variable can be associated with the set $N_{s\delta} = \{\mathrm{A}_{s\delta}, \mathrm{B}_{s\delta}, \mathrm{G}_{s\delta}, \mathrm{C}_{s\delta}, \mathrm{D}_{s\delta}, x(k)_{\min s\delta}, x(k)_{\max s\delta}, y(k)_{\min s\delta}, y(k)_{\max s\delta}\}$, $\delta \in \{0, 1\}$, which includes the matrices of equations (1), (2) and the constraint values (3), (4). Then the functioning of the system can be described through a logical-dynamical model in the form of a set of rules of the type If ... Then ... Otherwise .... If different events are not related, then the set of rules will only include rules of the form If $\delta_s$ Then $N_{s0}$ Otherwise $N_{s1}$. In a more complicated case, when chains of events are considered, some rules will be embedded into other rules.

Logical-dynamical models can be formally described as discrete hybrid automata (DHA). A special case of DHA is the class of piecewise affine (PWA) systems [8]. Such systems are also often called switched linear systems. According to paper [9], the system of logical conditions can be transformed into a system of integer linear inequalities, and the logical-dynamical model into a mixed logical-dynamical one (MDL). As shown in paper [9], the MDL model form encompasses a large class of hybrid dynamic systems. From the MDL model, one can, for example, turn to the equivalent PWA model. When implementing a hybrid MPC-algorithm, different types of logical-dynamical models can be used. Most often, PWA and MDL model formats are used.

## III. Hybrid Building Control System

Most of the existing implementations of the hybrid MPC algorithm are accomplished for the MATLAB/Simulink software package. The use of mathematical packages is justified by the fact that in the implementation of any MPC-algorithm, a large volume of operations with vectors and matrices is performed, and thus the problem of mathematical programming can be solved. In particular, to implement a hybrid MPC controller using the MDL model, it is necessary to solve the problem of mixed-integer programming.

The most popular tool for designing and simulating hybrid MPC controllers within MATLAB/Simulink is the Hybrid Toolbox [10] developed by Alberto Bemporad. Hybrid Toolbox supports MDL and PWA model forms. To describe the logical-dynamical models, a special modeling language HYSDEL is used. Hybrid Toolbox supports popular solvers for dealing with linear, quadratic and mixed integer programming problems, such as CPLEX, Xpress, Gurobi and others. Hybrid Toolbox can be used to manage rather complex hybrid dynamic systems. The disadvantages of the Hybrid Toolbox include some limitations associated with the language HYSDEL.

Another tool for MATLAB/Simulink, allowing the creation of MPC controllers for the management of hybrid dynamical systems is YALMIP [11]. YALMIP Toolbox uses only the PWA model format. Like Hybrid Toolbox, YALMIP supports a wide range of external solvers for linear, quadratic and mixed-integer programming.

A common downside of the tools considered is that they lead the task of predictive control of a hybrid dynamical system to the problem of mixed-integer programming, for the effective solution of which it is necessary to use external commercial solvers.

The authors propose an alternative approach to the solution of the problem of hybrid dynamical systems control. This approach uses the original logical-dynamical model, presented as a set of rules. A knowledge base of the production type is built from the rules of the model. The conditions of the production rules (IF-part) repeat the system of conditions of the original model, and the action parts (THEN-part) of the production rules define either the operation performed by the HVAC equipment and/or the MPC controller corresponding to the model defined by the $N_{s\delta}$ set. A diagram of the hybrid predictive climate and energy consumption control of the building is shown in Fig. 1.

In Fig. 1 events that occur during the functioning of the building (House Block) are classified by the Event Block and enter the rule database (Rule Base Block). The logical inference mechanism is implemented through the Rule Base and Inference Blocks. As a result of the logical inference, either the HVAC equipment control operation and/or the MPC variant corresponding to the current set of events are determined. The obtained MPC variant is selected from the controller database (MPC Controller Base) and transferred to the MPC Controller, where it is implemented to obtain the current control value. The received control signal is issued onto the HVAC equipment of the building.

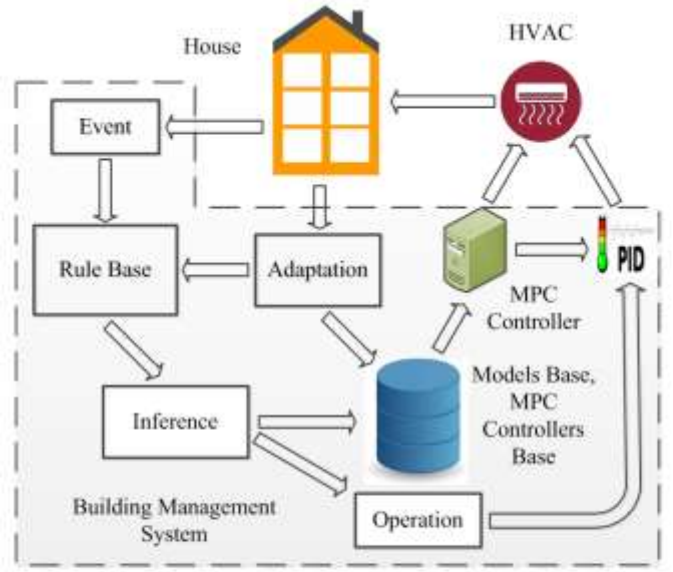


Fig. 1. Diagram of the hybrid predictive control system

If the set of events occurring during the functioning of a building is constrained and predetermined, then all MPC controllers corresponding to this set of events can be synthesized at the design stage. In this case, in calculating optimal control, the computational costs are minimized.

The proposed approach allows integrating the traditional HVAC-equipment, controlled on the basis of scenarios or the simplest control systems and the newest systems based on MPC controllers, into a single system. In doing so, some of the rules of the Rule Base Block can be used to implement HVAC control scenarios.

In addition, the proposed approach allows simultaneous use of both traditional and hybrid MPC controllers. The use of hybrid MPC controllers can be useful for reducing the number of synthesized MPC controllers. In this case, MPC Controller Block should be able to perform both traditional and hybrid MPC-algorithms. Using multiple hybrid MPC controllers may be more beneficial than using a single hybrid MPC controller.

An adaptation mechanism (Adaptation Block) can be supplied into the system proposed by the authors. It allows adding a response to new events not yet registered in the system. This mechanism allows the user to add new rules to the rules database, as well as synthesize and add new MPC controllers. This will make the system flexible and easily expandable.

## IV. Simulation Results

To test the proposed approach, the authors carried out computer simulation in the MATLAB/Simulink environment. The creation of a computer model of the hybrid control system greatly simplified the appearance of the Multiple MPC block within the new versions of the Simulink system. It allows prompt switching from one MPC controller to another during the simulation process. The list of the used MPC controllers is entered as an array into the corresponding parameter of the Multiple MPC block.

The model described in [7] was used as a model of the microclimate. The climate control system should maintain a temperature of 144 $m^2$ room, which include four brick walls, a concrete floor, a ceiling and two windows, at 20 °C. The temperature was measured to within 0,5 °C. The change in the temperature of the outdoor environment was modeled by a smooth periodic function with an amplitude of 3 °C and a central value of 12 °C. The main regulating effect used to maintain a given thermal regime in the rooms is the change in the temperature of the heat carrier within the system of water heating. The temperature is controlled by the MPC controller. The integral quadratic criterion was used. The control and output variables were constrained. Their values did not change during the simulation.

The following four events were stipulated In the process of simulation:

- switching on/off the circulation pump of the heating system;
- switching on/off the ventilation system fan;
- turning on/off the "warm floor" system;
- opening the windows in the room.

For the total of four events, sixteen different variants of events occurrence are possible, including the basic variant corresponding to the absence of all events. Therefore, sixteen variants of type (1), (2) models were prepared for carrying out the experiments as well as sixteen variants of MPC controllers synthesized.

Fig. 2 and Fig. 3 show the results of numerical experiments with the model. The dashed line in Fig.2 & Fig 3 shows the system response for the basic version of the MPC controller. The solid line in Fig. 2 shows a graph of the transient process for the event-sensitive MPC controller which monitors switching on the "warm floor", and Fig. 3 for the event-sensitive MPC controller, which handles turning on the "warm floor" system and the fan of the air supply system.

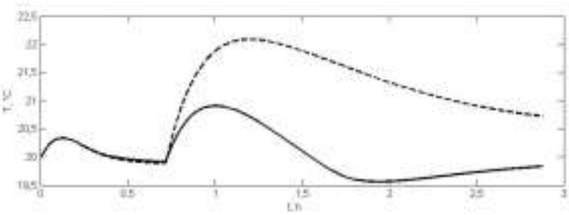

Fig. 2. System responses for the basic version of MPC controller and MPC controller handling one event

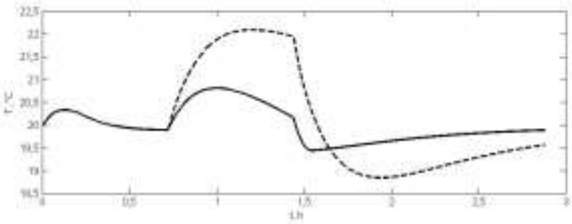

Fig. 3. System responses for the basic version of MPC controller and MPC controller handling two events

It can be seen that the quality of the system response for event-sensitive MPC controllers is much better.

## V. Conclusions and future research

This paper is devoted to the system of hybrid predictive control of microclimate and energy consumption within a building. The main advantage of the approach suggested by the authors is using both a traditional HVAC-equipment, managed on the basis of scenarios or the simplest control systems, and the newest MPC controllers within a single system. Another advantage comprises a simpler procedure for synthesizing MPC controllers, which does not bring about the problem of mixed-integer programming.

The downside of the proposed approach is the fact that as the number of significant events increases, the number of rules, the number of models variants and the number of variants of MPC controllers grow, accordingly, very rapidly. Reduction of the number of rules can be achieved through their analysis and the exclusion of rules containing events, the simultaneous occurrence of which is almost impossible. The use of hybrid MPC controllers reduces the number of variants for MPC controllers.

In the future, it is planned to include not only HVAC equipment into the hybrid predictive control system, but also the equipment of other building engineering systems, for example, the building security system. It is also necessary to study in more detail the impact of different kinds of equipment on each other, as well as the issues of ensuring the bumpless transfer when switching from one mode to another.

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