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Model predictive control of room temperature with disturbance compensation

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This paper deals with temperature control of multivariable system of office building. The system is simplified to several single input-single output systems by decoupling their mutual linkages, which are separately controlled by regulator based on generalized model predictive control. Main part of this paper focuses on the accuracy of the office temperature with respect to occupancy profile and effect of disturbance. Shifting of desired temperature and changing of weighting coefficients are used to achieve the desired accuracy of regulation. The final structure of regulation joins advantages of distributed computing power and possibility to use network communication between individual controllers to consider the constraints. The advantage of using decoupled MPC controllers compared to conventional PID regulators is demonstrated in a simulation study.

K e y w o r d s: decoupling, disturbance compensation, generalized predictive control, zone regulation, building management system

1 Introduction

Quality of zone regulation of temperature has a huge impact to total consumption of energy of the building and also to ensuring a suitable environment for work. The most common way of ensuring hygienic comfort in offices is the using of a central air handling unit, which delivers fresh air of the required flow and temperature. Centrally supplied air is then adjusted to the desired temperature by the end members (fancoils, beams). According to used technology, thermal comfort can be ensured by heat flow provided by ventilation or heat transfer provided by radiators or convectors. Incorrectly set equithermal curves (based on outside temperature), which determine the temperature of heating water for radiators often cause regulatory problems. Difficulties are also appearing by using fancoils without possibility to continuously change the fan speed, by beams without regulation flap or by using control elements which have slow response, which is common with actuators of the control valves. This thermal system with slow dynamics is often accompanied by disturbance in the form of an open window or a sudden change of outside temperature. A significant influence of neighbouring offices to accuracy of regulation and energy saving is often omitted. Nowadays the main motivation to overcome these regulatory problems is to reduce the energy load on the environment. For this purpose many types of regulation have been presented in literature. Some of these approaches are focused on tuning of parameters of PID regulators, which are often equipped with feedforward compensators or anti-windup technique. Some methods use neural networks [1] or fuzzy logic [2]. Searching for optimal gens throw generations is used in genetic algorithms [3]. Due the ability to apply the known future setpoint and possibility to include measured disturbance to control process, model predictive control (MPC) was used for this purpose. MPC strategy is often used for temperature control in office buildings, because it allows integrating a weather forecast in order to eliminate disturbance. Effect of disturbance to system which is regulated by MPC regulator is evident, mainly in case, when slow control members are used. The most common method is a simple feedforward compensator. To create effective compensator is necessary to know the dynamics between disturbance and process output and also dynamics of a regulated system [4]. If the dynamics of system and disturbance is described by transfer function, ideal compensator is formed by division of these two functions with opposite sign. This paper presents use of this compensator at a precise time in MPC structure. During operation of the compensator, it is necessary to adjust weighting coefficients of MPC regulator. To ensure stability of system, shifting of the desired temperature vector is used. This method is based on knowledge of occupancy profile. Occupancy profile is often used in various approaches, which are trying to ensure minimal energy consumption during working time [5]. One of the most popular MPC algorithm is General Predictive Control (GPC), which is also used in this paper. This algorithm can be used for a wide range of processes, including those with simple dynamics or systems with time delay, unstable systems or system with more complex dynamics [6]. This paper discusses the issue of temperature regulation in separated offices of building base on MPC strategy and it is organized as follows. A model of six neighbouring rooms in the office building and based of heat transfer is described and use of decoupling of mutual interactions between neighbouring offices to simplify a MIMO system are discussed. Theoretical base of GPC algorithm with focusing on the effect of disturbance is presaented. Usage of feedforward

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compensator and the effect of weighting coefficients is also discussed and simulation example is shown below. The use of the occupancy profile and to shifting of desired temperature vector is clarified as well as the effect of weighting coefficients to stability of control system.

2 Model of thermal system

To achieve a sufficient quality of control by the MPC controller, it is necessary to apply a precise model of system and disturbance. For description of a small part of office building, a model of six neighbouring offices was used. Five offices are in contact with air temperature throw glass facade. One of these offices (central office) has a common surface for each of others. Each office is described by equation base on law of conservation of thermal energy. The temperature change rate is dependent on heat quantity entering into or leaving form object, which has heat capacity, by convection and conduction in our case, where m is weight of the air mass, c_p is heat capacity of air and H_i are heat fluxes. Heat fluxes in model are represented by flow from one liquid to another throw surface and by flowing fluid

$$mc_p \frac{\mathrm{d}T}{\mathrm{d}t} = \sum_{j=1}^{N} H_i. \tag{1}$$

For each office in model, it is possible rewrite (1) as

$$\begin{aligned} pV\frac{\mathrm{d}T}{\mathrm{d}t} &= K + k_0 S_0 (T_0 - T) + \\ &+ c_p \rho Q (T_u - T) + \sum_{i=1}^{5} k_i S_i (T_i - T), \end{aligned} \tag{2}$$

where ρ is air destiny, V is office volume, K is constant, which could be represented as power of additional heater, k_0 is heat transfer coefficient of glass, S_0 is surface of glass with contact with outside air, $T - T_0$ is outside temperature, Q is air flow, which is ensure by air handling unit, k_i is heat transfer coefficient of wall or concrete, S_i is surface of neighbouring office (wall, ceiling or floor), T_i is room temperature of neighbouring office (T_i is considered as constant, when heat flux throw common wall with central office is not described) and T_u is temperature of incoming air from ventilation. The first term of (2) can be considered as constant and together with difference of outside temperature are regarded a disturbance. Air flow Q is constant and offices are not pressurized or depressurized. From regulatory view room temperature T is considered as a state and output variable and temperature of incoming air T_u as control variable. From (2) is obvious that six systems have mutual interconnections and they form a MIMO system. Change of room temperature caused by changing desired temperature or by disturbance generates a control reaction, which affects also adjacent office. The bigger is adjacent surface and the worse thermal insulation properties are, the more evident effect is. The effect of the neighbouring offices naturally decreases if the gain of system grows (increase airflow, increased enthalpy of incoming air) or disturbance appears. The appearance of disturbance has a much more significant influence on the final quality of regulation in comparison with the influence of adjacent rooms, but every energy saving is nowadays important. To avoid undesired influencing, the method from nonlinear control was used. The use of this method is conditioned by reliable communication between local regulators and by exact values of a heat transfer coefficient.

3 Decoupling

Basic problem of multivariable systems is the dependence of output variable from multiple inputs. The aim is to remove interconnections between subsystems and to ensure the conditions in which the action variable (the temperature of the incoming air) affects only the room temperature of the controlled zone. Decoupling is a well-known method which is used mainly in non-linear system, when it is necessary to remove nonlinearities from the control system. The principle is based on the creation of a control signal u which, when entering the system, eliminates undesirable components. The equation (2) shows that the relative order of the system is one. Relative order tells us how many times it is necessary to derive output of system ($y = T$) to get functional dependence from input ($\dot{y} = \dot{T} = f(T_u)$). This principle is applicable when relative order is finite. Before writing final form of control variable u, it is necessary to determine desired dynamics of the system. It is desirable to system looks like system of first order with time constant T_c and gain k_c. For new input v, transfer function looks as follows

$$F_s = \frac{Y(s)}{V(s)} = \frac{K_c}{T_c s + 1}. \tag{3}$$

After merging constants and substituting (2) in (3), control signal u, which eliminate interconnection of adjacent offices takes following form,

$$u = \frac{K_c}{T_c b_A} - \frac{1 - T_c c}{T_c b_A} y - \sum_{i=2}^{5} \frac{c_i}{b_A} y_i, \tag{4}$$

where c, c_i, b_A are constants y_i are a temperature of adjacent rooms (for offices except central office $i = 1$), T_c is the time constant and K_c is the gain. Constants considered as disturbance are not compensated by input signal. Time constant and gain of system should be valuated naturally, from state of the system, where no interconnection has influence to system. From right side and from the third member of left side of (2) we can determinate time constant $T_c = V/Q$ and gain $K_c = 1$.

Figurte 1 shows time responses of room temperatures of adjacent offices during setpoint steps. Every office has the same dimensions ($a = 5.5m, b = 2.5m, c = 3.5m$)

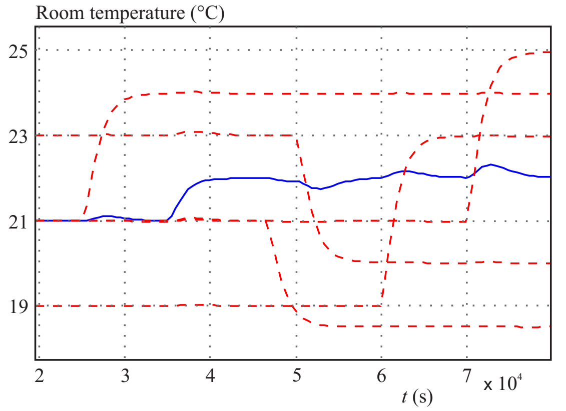

Fig. 1. Time responses of room temperature without decoupling

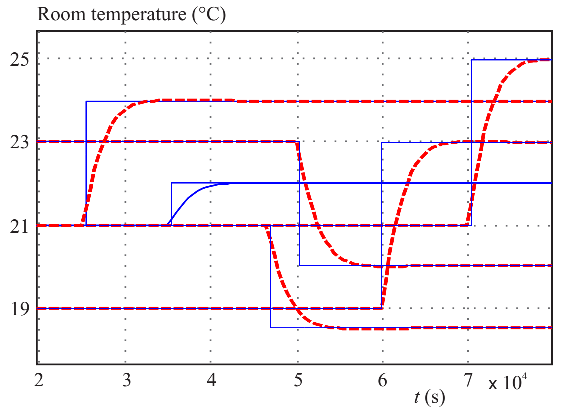

Fig. 2. Time responses of room temperature with decoupling

and air flow is considered constant $Q = 100\,\mathrm{m}^3/\mathrm{h}$, what corresponds to a double exchange of air per hour in the office. Significant deflections of room temperature of central office (blue line) are appearing and the problem is that local regulator starts to react after detection of non-zero control deviation of this zone, but not after changing of room temperature of neighbouring office. After elimination of mutual connection, in Fig.2 it is possible to observe significant improvement in regulation.

Room temperature of central office (blue line) is not influenced by steps of desired temperature of adjacent offices, and the temperature of neighbouring offices (red dashed line) is not changed during the step of desired value of central office. Elimination of these deflections ensures accuracy of regulation and reducing final energy consumption. These independent systems behave like systems of first order with designed gain and time constant and it is possible to use any type of control on them. Due to many benefits, MPC was used for this purpose.

4 Model predictive control

The base idea of predictive control is computing of control input by solving an optimal problem throw given time horizon, when only the first computed value of input is used. Calculation is based on minimizing of objective function,

$$J = \sum_{j=N_1}^{N_2} \lambda_y(j)\left[\hat{y}(k+j|t) - w(k+j)\right]^2 + \\ x + \sum_{i=1}^{N_u} \lambda_u(j)\left[\Delta u(k+j-1)\right]^2, \tag{5}$$

which penalizes tracking errors and control efforts [4], where $N-1$ and $N-2$ are the minimum and maximum prediction horizon, N_u is control horizon, $\Delta u(k+j-1)$ is a future control increment sequence, $\hat{y}(k+j|t)$ is an output prediction sequence, $w(k+j)$ is future λ_y and λ_u are the weighting coefficients. These coefficients are usually constant along the control horizon and they have impact to quality and stability of the system. Possibility to include future reference signal to control algorithm seems to be one of the most beneficial elements of this approach. The maintenance of building struggles with optimal timing of preparation of heating water, domestic hot water or turning on technologies for secure of thermal comfort of people. The maintenance often uses their own experience to optimize this process, what leads to unnecessary waste of energy.

To achieve the optimal control action is used well-known CARIMA model modified by the vector of the measurable disturbance $v(k)$,

$$A(z)y(k) = z^{-d}B(z)u(k-1) + \\ + z^{-d_v}D(z)v(k) + \frac{C(z)}{\Delta}e(k), \tag{6}$$

where $A(z), B(z)$ and $D(z)$ are polynomials describing the system and disturbance respectively, d and d_v is number of steps of time delay, $\Delta = 1 - z$ and $e(k)$ is zero mean white noise. Polynomial $C(z)$ for simplification is considered to be equal to one. The result of solving two Diophantine equations (see [7] for details) leads to the following equations

$$\begin{aligned} &\hat{\mathbf{y}} = \mathbf{G}_f\mathbf{u}_f + \mathbf{V}_f\mathbf{v}_f + \mathbf{G}_p, \\ &\mathbf{G}_f = \mathbf{A}_f^{-1}\mathbf{B}_f, \quad \mathbf{V}_f = \mathbf{A}_f^{-1}\mathbf{D}_f, \quad \mathbf{G}'_p = \mathbf{G}_p + \mathbf{V}_p\mathbf{v}_p, \\ &\mathbf{G}_p = \mathbf{H}\mathbf{u}_p + \mathbf{S}\mathbf{y}_p, \quad \mathbf{V}_p = \mathbf{A}_f^{-1}\mathbf{D}_p, \\ &\mathbf{H} = \mathbf{A}_f^{-1}\mathbf{B}_p \quad \mathbf{S} = \mathbf{A}_f^{-1}\mathbf{A}_p, \end{aligned} \tag{7}$$

where matrices $\mathbf{A}_f, \mathbf{A}_p, \mathbf{B}_f, \mathbf{B}_p$ and $\mathbf{V}_f, \mathbf{V}_p$ are constant matrices created from coefficient of polynomials of system $\bar{A}(z)$, $\bar{B}(z)$ and polynomial of disturbance $D(z)$ Vector $\hat{\mathbf{y}}$ is sequence of future system outputs, $\mathbf{u}_f$ is composed of future control differences and $\mathbf{v}_f$ is vector of future measurable differences. Vectors $\mathbf{u}_p$ and $\mathbf{v}_p$ contain values from past. From (7) it is noticeable, that prediction of output is divided into two parts. The first part with index p is a system response on input from past (under the condition that last control input remains constant) free response and the second part is a system response on estimated future control inputs. After some manipulations and substituting (7) to (5) it is possible to minimize cost function J with respect to $\boldsymbol{u}$, what means $\frac{\partial J}{\partial n} = 0$. The

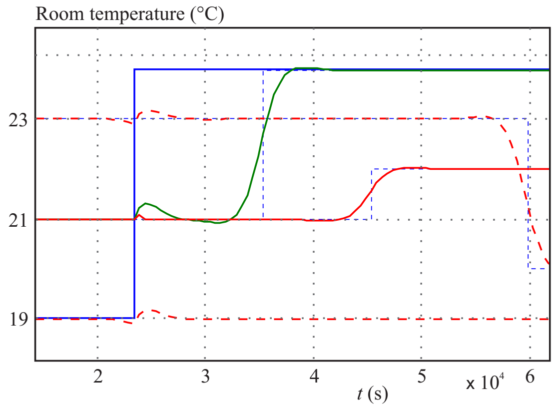

Fig. 3. Time response of room temperatue to disturbance, $\mathbf{\Lambda}_u > 0$

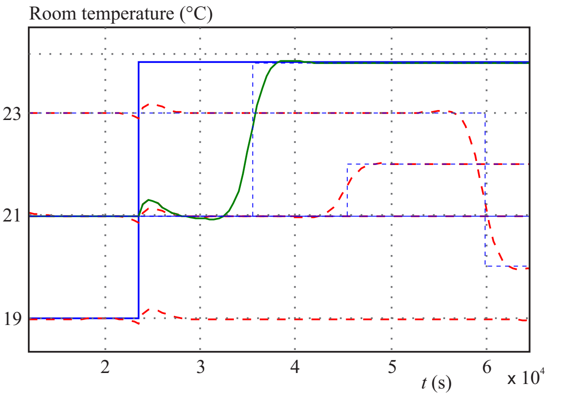

Fig. 4. Time response of room temperatue to disturbance, $\mathbf{\Lambda}_u > 0$

equation for computing the sequence of future control increments has the form

$$\mathbf{u}_f = -\mathbf{K}^{-1}\big(\mathbf{G}_f^\top \mathbf{\Lambda}_y \mathbf{S}\mathbf{y}_p + \mathbf{G}_f^\top \mathbf{\Lambda}_y \mathbf{H}\mathbf{u}_p + \mathbf{G}_f^\top \mathbf{\Lambda}_y \mathbf{V}_f \mathbf{v}_f - \mathbf{G}_f^\top \mathbf{\Lambda}_y \mathbf{w}_f\big), \quad \text{where:} \quad \mathbf{K} = \mathbf{G}_f^\top \mathbf{\Lambda}_y \mathbf{G}_f + \mathbf{\Lambda}_u\,, \tag{8}$$

where $\mathbf{\Lambda}_y$ and $\mathbf{\Lambda}_u$ and are diagonal weighting matrices and w_f is vector of future desired values. Equation (8) does not contain neither matrix $\mathbf{V}_p$ nor vector $\mathbf{v}_p$, because past values of measured disturbance are not considered. From the computed sequence of future control increments only the first is used and next control step is computed again from updated values.

For simulation purpose, the model of each from six independent systems and disturbance was described by discrete transfer functions respectively

$$F_s(z) = \frac{B(z)}{A(z)} = \frac{0.2524}{1 - 0.7476z}, \tag{9}$$

$$F_v(z) = \frac{D(z)}{A(z)} = \frac{0.02384}{1 - 0.7476z}. \tag{10}$$

Following parameters were set. Prediction horizon $N_2 - N_1 = 20$, control horizon $N_u = 20$, coefficient $\lambda_y = 50$, $\lambda_u = 80$ and simulation step equaled 500 s. A sudden change in outdoor temperature was considered a disturbance. In Fig. 3 is shown the time response of system outputs to disturbance. This figure shows differences between MPC regulators, which had implemented structure for elimination of disturbance influence (red dashed line) and MPC regulator, which structure does not include the disturbance (green line). The differences are not significant and MPC regulators do not achieve required elimination of measurable disturbance. The root of the problem is that MPC regulator does not behave as classical feedforward compensator. Typical feed forward structure can be created by dividing dynamics between disturbance input and system output $\frac{D(z)}{A(z)}$ by the dynamics between control input and system output $\frac{B(z)}{A(z)}$ [4], what leads to $\frac{D(z)}{B(z)}$. From (8) we can notice, that contribution of disturbances to future control increment is done by

$$\mathbf{u}_{fv} = -\mathbf{K}^{-1}\left(\mathbf{G}_f^\top \mathbf{\Lambda}_y \mathbf{V}_f \mathbf{v}_f\right) = -\left(\mathbf{G}_f^\top \mathbf{\Lambda}_y \mathbf{G}_f + \mathbf{\Lambda}_u\right)^{-1}\left(\mathbf{G}_f^\top \mathbf{\Lambda}_y \mathbf{V}\mathbf{v}_f\right). \tag{11}$$

It is obvious that in case of $\mathbf{\Lambda}_u = \mathbf{0}$ matrices $\mathbf{G}_f^\top$ and $\mathbf{\Lambda}_y$ would disappear and compensator would gain a classical form of feedforward compensator. This setting for matrix $\mathbf{\Lambda}_u$ causes aggressive control interventions and due to slow dynamics of some control elements, control intervention may not be realizable. For this reason, mentioned setting $\mathbf{\Lambda}_u = \mathbf{0}$ is used in regulation only when the controller detects non-zero member of vector of future disturbance increment along the predictive horizon. Matrix $\mathbf{\Lambda}_u$ remains zero also for certain time (equals predictive horizon) from last detection of non-zero disturbance increment. Figure 4 shows significant improvement of disturbance elimination after using mentioned setting (red line).

It is important to realize, that correct elimination of disturbance is sensitive to accuracy of dynamics description and MPC regulator is not always successful, mainly in system with constraints, where desired aggressive control input is limited.

5 Future occupancy

Comparing Fig. 2 and Fig. 4 it is possible to notice system reaction to steps of required values. It is obvious that MPC regulator starts to react earlier, just in time, which is necessary to achieve desired value, up to cost function. The behaviour of MPC regulator is influenced by adjusting of weighting coefficients $\mathbf{\Lambda}_y$ and $\mathbf{\Lambda}_u$. Higher value of $\mathbf{\Lambda}_y$ together with lower value of $\mathbf{\Lambda}_u$ accuracy of tracking desired value, the opposite situation leads to saving of action members and energy. As was mentioned disturbance elimination relates to a total reduction of coefficient $\mathbf{\Lambda}_u$. Together with an improperly set value of coefficient $\mathbf{\Lambda}_y$, it can lead to instability of system. Control law (8) can be expressed by a standard linear form of RST

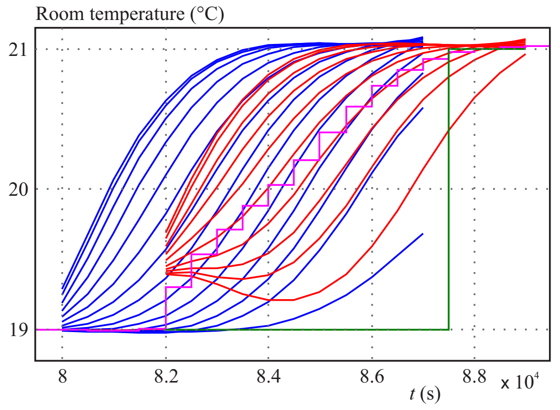

Fig. 5. Detail on sets of predictive output of system

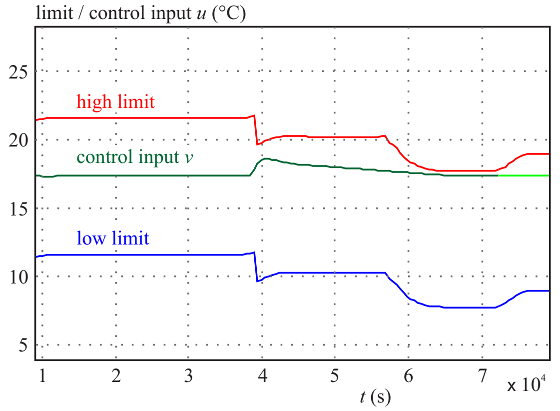

Fig. 7. Changing constraints of control signal v

control law or form supplemented by polynomial $Q(z)$, which represents a disturbance

$$R(z)\Delta u(k) = S(z)y(k) + \\ + T(z)w(k+j) + Q(z)v(k+j). \tag{12}$$

After substituting (12) to (6) it is possible to get the equation of closed control circuit with predictive control

$$\left[\bar{A}(z)R(z) - B(z)S(z)\right] y(k) = \\ = T(z)w(k+j) + (Q(z) + D(z)v(k+j)) . \tag{13}$$

The stability of the system can be investigated from the characteristic equation according to its roots

$$\bar{A}(z)R(z) - B(z)S(z) = 0. \tag{14}$$

Polynomials $R(z)$ and $S(z)$ contain weighting coefficients, which choice is directly responsible for stability of the system. As it was mentioned, in some cases it is necessary to reach desired values (room temperature) in certain time. This requirement leads to an excessive increase of the coefficient $\boldsymbol{\Lambda}_u$, what may result in system instability. Our approach uses occupancy profile to avoid this problem. Occupancy profile is basis time schedule, which is set according to working time. During this time accuracy of tracking desired value.is strictly required. To secure the stability of the system, weighting coefficients

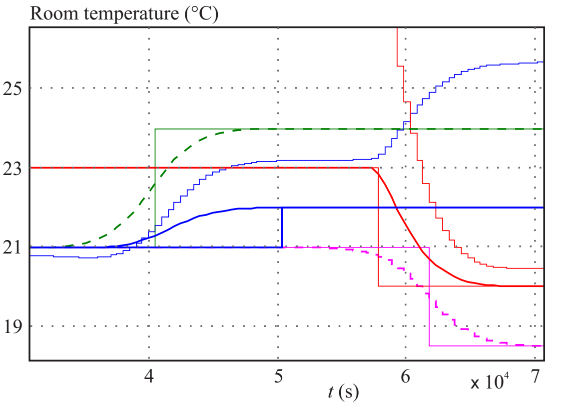

Fig. 6. Time responses of room temperatue with and witout shiftingT desired value

are not changing (except of appearance of disturbance), but the vector of required temperature is shifted for optimization purpose. Every computing step is calculated future output (according actual values and future desired value) and predictive outputs for desired value shift to the future. In our case is calculated 15 predictions of the output variable. In Fig. 5 it is possible to see two sets of predicted values in different time (blue and red lines).

Differences between predicted values and real future desired value (green line) are penalized by coefficients δ_y (only if the vector of occupancy $\boldsymbol{\gamma}$ is non-zero) and control increment by δ_u.From these possibilities is chosen prediction with minimal value of cost function (15). The first element of the control increment vector of the best prediction is used and calculation is repeated. The result of this approach is the achievement of desired temperature exact in time, when it is required (magenta line). Demands for computational power increase, but compared with the methods, which use whole network for optimizing [8], this approach is relatively simple and applicable for simple zone programmable regulators with communication. Figure 6 shows a comparison of used method (blue and red line) with classical MPC regulator (green and magenta dashed In Fig. 6 is also shown time response of control input (discrete lines) and steps of desired values.

$$J(i) = \sum_{j=N_1}^{N_2} \delta_y |\hat{y}(i,j) - w| \gamma(j) + \sum_{j=1}^{N_u} \delta_u |\Delta u(i,j)|. \tag{15}$$

6 MPC regulator comprising the constrains

In practice, almost every control system must focus on limitation of process variables. The most evident constraint associated with temperature control is the rate of change of system output and limitation of control input. Basic limitation of control input (temperature of incoming air) is a range of temperature between 15 °C and 35 °C. It is also sometimes necessary to keep the maximal difference between room temperature and temperature of incoming air. In some special situation, it is also necessary not to exceed the rate of change of output temperature (drying of wet walls). Including of constraints to the system requires solving the problem of quadratic programming with standard form

$$\min \mathbf{x}^\top \mathbf{H}\mathbf{x} - \mathbf{g}^\top \mathbf{x}, \qquad \mathbf{C}\mathbf{x} \geq \mathbf{c} \tag{16}$$

$$C = [\mathbf{I}_L, -\mathbf{I}_L, \mathbf{I}_{ch}, -\mathbf{I}_{ch}, \mathbf{G}_f, -\mathbf{G}_f]$$

$$\mathbf{c}^\top = \begin{bmatrix} \begin{bmatrix} u_{\min} - u(k-1) \\ \cdot \\ u_{\min} - u(k-1) \end{bmatrix} & - \begin{bmatrix} \Delta u\_\max \\ \cdot \\ \Delta u\_\max \end{bmatrix} \\ \begin{bmatrix} u_{\max} - u(k-1) \\ \cdot \\ u_{\max} - u(k-1) \end{bmatrix}, & - \begin{bmatrix} \Delta u\_\max \\ \cdot \\ \Delta u\_\max \end{bmatrix}, \\ \begin{bmatrix} \Delta y_{\min} - y_0 \\ -\Delta y_{\max} + y_0 \end{bmatrix} \end{bmatrix}, \tag{17}$$

where $\mathbf{H} = \mathbf{G}_f^\top \mathbf{\Lambda}_y \mathbf{G}_f + \mathbf{\Lambda}_u$ is Hesse matrix, identical to gain $\mathbf{K}$ from (8), $\mathbf{g} = -2(\mathbf{y}_0 - \mathbf{G}_f^\top \mathbf{\Lambda}_y \mathbf{w}_f)$ is a vector of gradient which includes free response of system $\mathbf{y}_0 = \mathbf{G}_f^\top \mathbf{\Lambda}_y \mathbf{S}\mathbf{y}_p + \mathbf{G}_f^\top \mathbf{\Lambda}_y \mathbf{H}\mathbf{u}_p$. Matrix of constants $\mathbf{C}$, and vector of constants $\mathbf{c}$ (which must be actualized every step of calculation) are defined by (17). Problem of quadratic programming is a well-known issue and it is beyond the interest of this paper (see [7], [9] for details). Addition of this paper for this problem is a way of actualizing of constants, of matrix $\mathbf{c}$. Individual MPC regulator generates optimal prediction of output variable according section 4 and 5. Values are sent throw communication network to regulators of adjacent offices and control inputs are computed according (4). Respecting limitations of control signal u, the limitation for signal v is calculated for every regulator (small addition of limitation from neighbouring rooms is now included). These updated limits are used for recalculation of control signal according (16). This procedure is repeated every computing step. Figure 6 shows changing limitations of control signal v, when limitation of real control signal was set to range between 15 °C and 24 °C.

7 Conclusion

Zone temperature regulation is an interesting regulatory problem, which calls for overcoming of difficulties connected with mutual interconnection of neighbouring offices. For this purpose, decoupling was used, a method known mainly in nonlinear systems. To be able to use this method, it is necessary to describe the dynamics of the system precisely. To ensure quality and stability of regulation, MPC regulator was used. Frequent occurrence of disturbance requires include model of disturbance into the control algorithm. By the setting of weighting coefficient was possible to eliminate measured disturbance. To secure precise tracking of desired temperature in a certain time, the occupancy profile was introduced. Occupancy profile was added by special type of shifting required values with the effort of the most precise regulation. Constraints of input and output variables were included to control algorithm via solving problem of quadratic programming with updating of vector of constraints. In general, it is possible to summarize, that MPC regular is suitable choice for zone temperature control. It allows to include elimination of measurable disturbances, constraints and very important future occupancy profile, which can secure energy saving.

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Peter Hubinský was born in 1962 has received MSc and PhD degrees from Faculty of Electrical Engineering of the Slovak University of Technology in 1985 and 1992, respectively. After shorter work in praxis in industrial robotics he has returned and worked in the role of assistant, since 1999 Assoc. Professor and 2011 as a full Professor in area of robotics, mechatronics and dynamic system control. He cooperated for long period with foreign partners mainly in Germany. His current research interests are including resonance free control of mechatronic systems, mobile robot visual control and other related areas.