$$\begin{aligned} y(k) = &-a_1 y(k-1) - a_2 y(k-2) + \\ &+ b_1 y(k-1-d) + b_2 y(k-2-d) + n_c(k) \end{aligned} \tag{23}$$

where $n_c(k)$ is the random non-measurable component. The vector of parameter model estimates is computed by solving equation (19)

$$\hat{\boldsymbol{\Theta}}^T(k) = \begin{bmatrix} \hat{a}_1 & \hat{a}_2 & \hat{b}_1 & \hat{b}_2 \end{bmatrix} \tag{24}$$

and is used for computation of the prediction output

$$\begin{aligned} \hat{y}(k) = &-\hat{a}_1 y(k-1) - \hat{a}_2 y(k-2) + \\ &\hat{b}_1 u(k-1-d) + \hat{b}_2 u(k-2-d) \end{aligned} \tag{25}$$

The quality of identification can be considered according to error, i.e. the deviation

$$\hat{e}(k) = y(k) - \hat{y}(k) \tag{26}$$

In this paper, the error was used for suitable choice of the time-delay dT_0. The LSM algorithm (19) – (22) is computed for several time-delays dT_0 and the suitable time-delay is chosen according to quality of identification based on the prediction error (26).

Except LSM the MATLAB function from the Optimization Toolbox

$$x = \text{fminsearch}('\mathit{name\_fce}', x_0) \tag{27}$$

was also used for the off-line process identification. This function find minimum of an unconstrained multivariable function using derivative-free method. Algorithm “fminsearch” uses the simplex search method of [28]. This is a direct search method that does not use numerical or analytic gradients.

It is obvious that the quality of time-delay systems identification is very dependent on the choice of a suitable input exciting signal $u(k)$. Therefore the MATLAB function from the System Identification Toolbox

$$u = \text{idinput}(N, \mathit{type}, \mathit{band}, \mathit{levels}) \tag{28}$$

was used [29]. This MATLAB code generates input signals u of different kinds, which are typically used for identification purposes. N determines the number of generated input data. *Type* defines the type of input signal to be generated. This argument takes one of the following values:

type = 'rgs': Gives a random, Gaussian signal.
type = 'rbs': Gives a random, binary signal. This is the default.
type = 'prbs': Gives a pseudorandom, binary signal.
type = 'sine': Gives a signal that is a sum of sinusoids.

6.2 Recursive Identification Algorithm

The regression (ARX) model of the following form

$$y(k) = \boldsymbol{\Theta}^T(k)\boldsymbol{\Phi}(k) + n_c(k) \tag{29}$$

is used in the identification part of the designed controller algorithms, where

$$\boldsymbol{\Theta}^T(k) = \begin{bmatrix} a_1 & a_2 & b_1 & b_2 \end{bmatrix} \tag{30}$$

is the vector of model parameters and

$$\boldsymbol{\Phi}^T(k-1) = \begin{bmatrix} -y(k-1) & -y(k-2) & u(k-d-1) & u(k-d-2) \end{bmatrix} \tag{31}$$

is the regression vector. The non-measurable random component $n_c(k)$ is assumed to have zero mean value $E[n_c(k)] = 0$ and constant covariance (dispersion) $R = E[n_c^2(k)]$.

The digital adaptive GPC controller uses the algorithm of identification based on the Recursive Least Squares Method (RLSM) extended to include the technique of directional (adaptive) forgetting. Numerical stability is improved by means of the LD decomposition [30], [31]. This method is based on the idea of changing the influence of input-output data pairs to the current estimates. The weights are assigned according to amount of information carried by the data.

When using the adaptive principle, the model parameter estimates must approach the true values right from the start of the control. This means that as the self-tuning algorithm begins to operate, identification must be run from suitable conditions – the result of the possible *a priori* information. The role of suitable initial conditions in recursive identification is often underestimated.

6.3 Off-Line Identification of Laboratory Heat-Exchanger

The dynamic off-line model of the laboratory heat exchanger was obtained from processed input (the power of a flow heater P [W]) and output (the temperature of a T_2 [^{o}C] of the cooler) data (see Fig. 1). The input signal $u(k)$ was generated using the MATLAB function “idinput” and discrete parameter estimates of model (25) for sampling period T_0 = 100 s and time-delay T_d = 200 s were computed using off-line LSM and MATLAB function “fminsearch”.

The graphical variable courses of individual identification experiments are shown in Figs. 5 – 7.

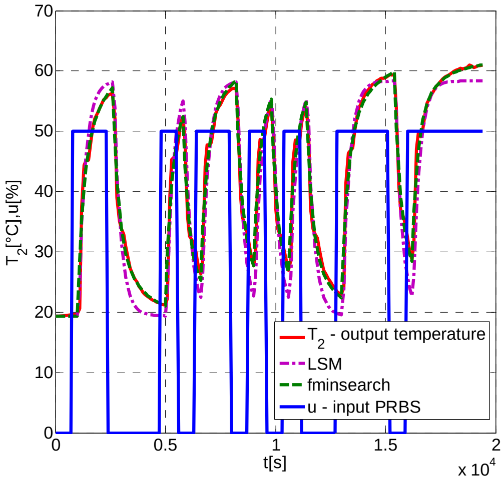

Fig. 5. Identification results: input PRBS

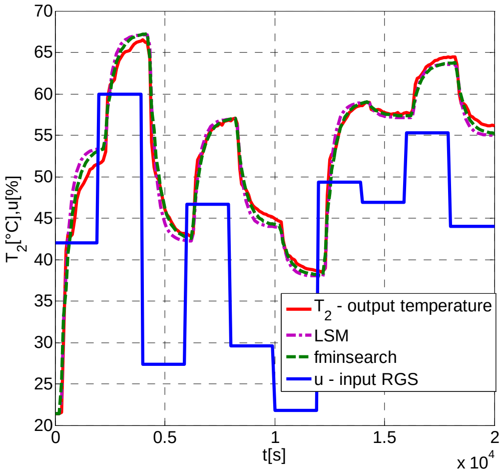

Fig. 6. Identification results: input RGS

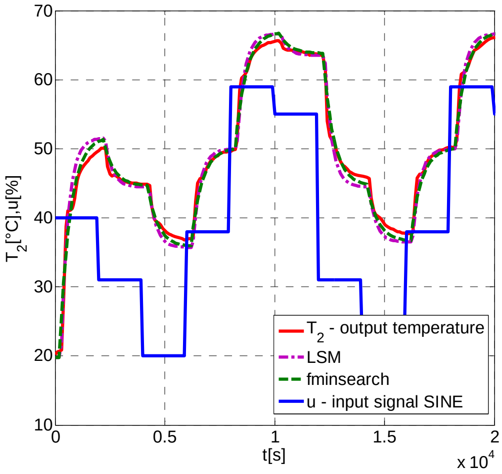

Fig. 7. Identification results: input SINE

Six discrete models which were obtained from individual experiments and criterions of identification quality are presented in [32]. The real output variable T_2 and the modelled output variables of the individual models were compared using criterion of identification quality

$$S_y = \frac{1}{N}\sum_{k=1}^{N}\left[y(k)-\hat{y}(k)\right]^2 \qquad (32)$$

where $\hat{y}(k)$ is the predicted output and the estimate of static gain is

$$\hat{K}_g = \frac{\hat{b}_1+\hat{b}_2}{1+\hat{a}_1+\hat{a}_2} \qquad (33)$$

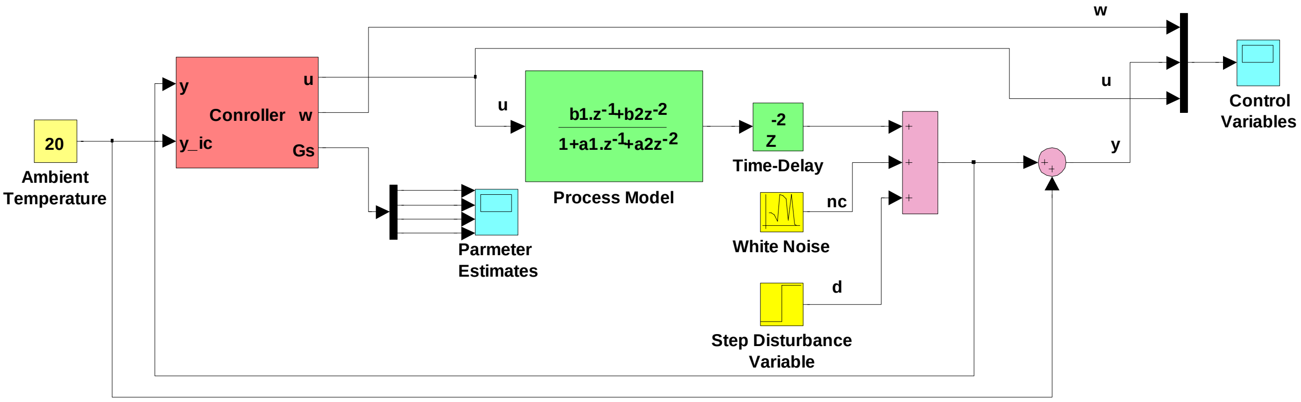

Fig. 8. General SIMULINK control scheme

7 Predictive Control of Heat Exchanger

On the basis of identification experiments, the discrete model in the form

$$G\left(z^{-1}\right) = \frac{0.1088z^{-1}+0.1964z^{-2}}{1-0.0855z^{-1}-0.5157z^{-2}}z^{-2} \qquad (34)$$

was used for simulation verification of the designed predictive algorithm. A typical

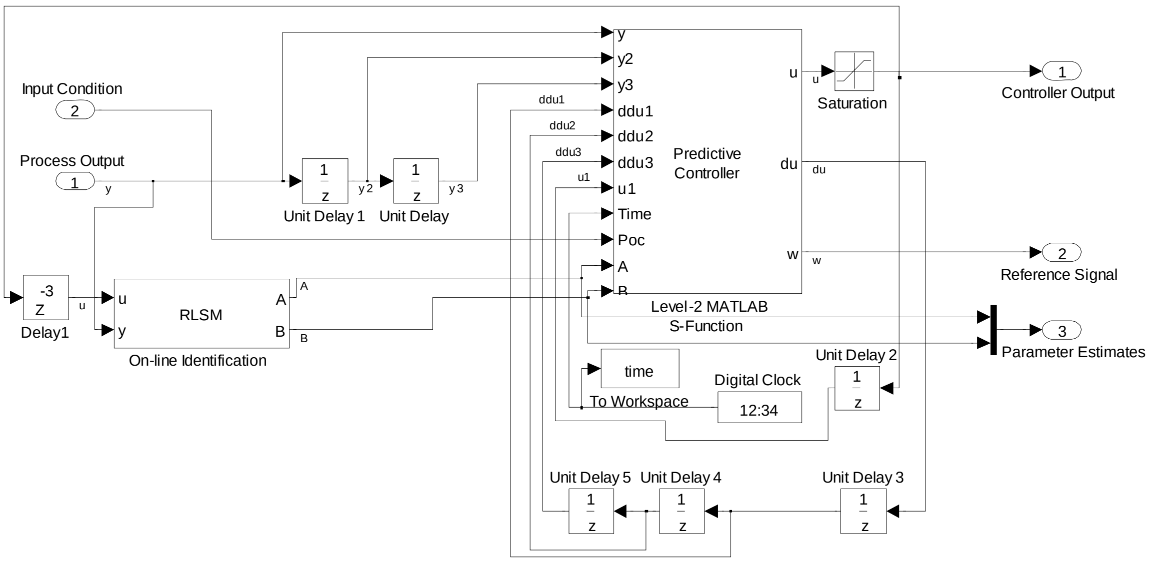

Fig. 9. SIMULINK scheme of subsystem Predictive Controller

SIMULINK scheme used for predictive control of second order systems with time-delay of two sample steps is depicted in Fig. 8. The general scheme consists of the constant block for setting of the Ambient Temperature, the Controller and Process Model with the Time-delay block. The SIMULINK scheme is completed by the White Noise Generator and the Step Disturbance. The main block Predictive Controller contains generating of the reference signal, the recursive identification part and own predictive controller (see SIMULINK scheme – Fig. 9). Following individual horizons were used:

$$N_1 = d + 1 = 3,\ N_2 = 30,\ N_u = N_2 - d = 28\,.$$

Two real-time control experiments for different values of the weighting factor λ were realized:

1) The model parameters of (32)

$$\hat{\boldsymbol{\Theta}}^T(0) = [-0.0855 \quad -0.5157 \quad 0.1088 \quad 0.1964]$$

were used as the initial model parameter estimates for the real-time control, it comes to this, that *a priori* information was used. Therefore elements of the main diagonal covariance matrix were chosen $C_{ii}(0) = 10^{-3}$ (an assumption, that the dispersions of the parameter estimates are in a narrow interval). The courses of the control variables are well including of the initial control interval – see Fig. 10. The evolution of the model parameter estimates in the individual sampling steps is shown in Fig. 11.

2) The model parameter estimates were chosen without *a priori* information

$$\hat{\boldsymbol{\Theta}}^T(0) = [-0.0855 \quad 0.5157 \quad 0.1088 \quad 0.1964]$$

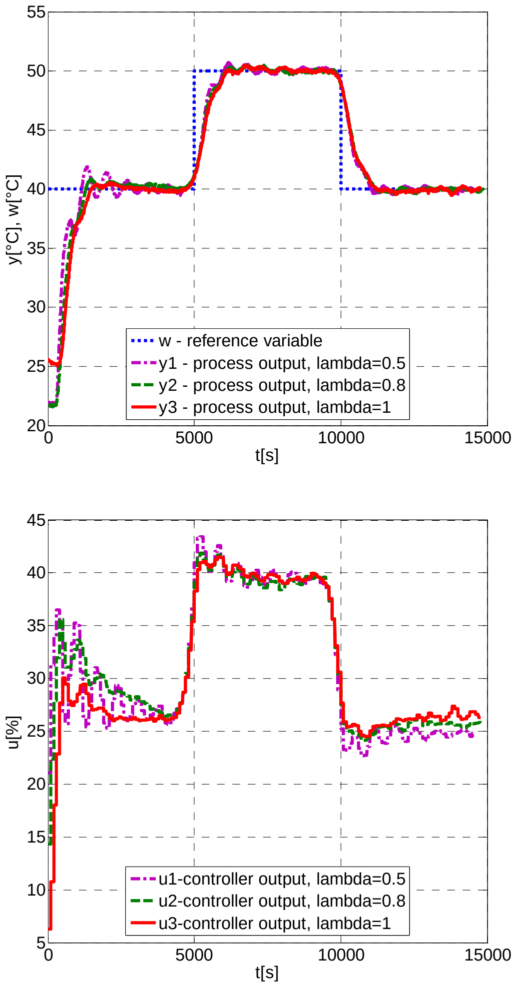

Fig. 10. Process control with *a priori* information

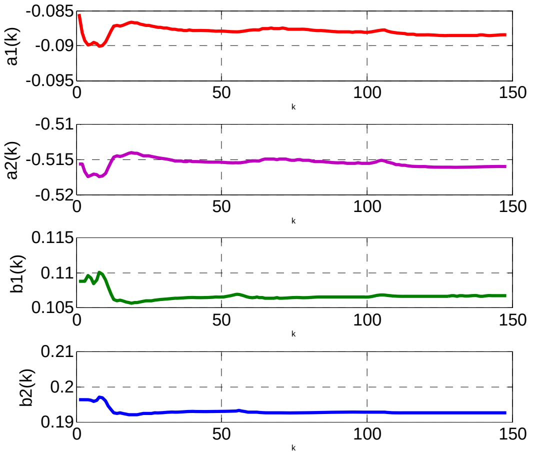

Fig. 11. Evolution of model parameter estimates, $C_{ii}(0) = 10^{-3}$

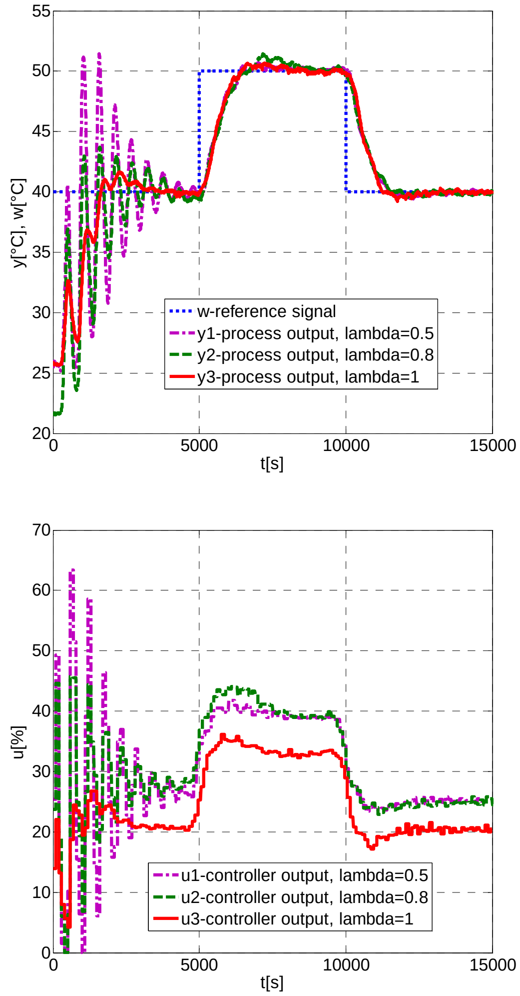

Fig. 12. Process control without *a priori* information

(by parameter estimate $\hat{a}_2$ was changed polarity). Therefore elements of the main diagonal covariance matrix were chosen $C_{ii}(0) = 10^3$ (an assumption, that the dispersions of the parameter estimates are in a wide interval). The courses of the control variables oscillate in the initial control interval, when the model parameter estimates are converged, the quality of the control process is very good – see Fig. 12. The evolution of the model parameter estimates in the individual sampling steps is shown in Fig. 13.

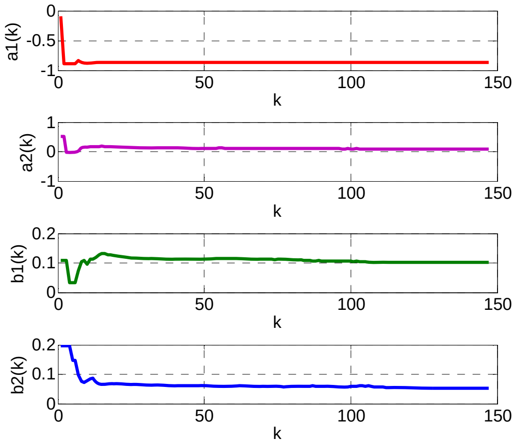

Fig. 13. Evolution of model parameter estimates, $C_{ii}(0) = 10^3$

The dependence of the process variables (process and controller outputs) on the weighting factor λ is obvious from Figs. 10 and 12. The experimental control results were influenced by variation of the outdoor temperature (see e.g. the courses of the control variables for $\lambda = 1$ in Fig. 12, where the experiment was realized for low outdoor temperature).

Some journal or conference papers deal with MPC of heat exchangers. Robust MPC of a heat exchanger network is designed and verified by simulation in [33]. The subject of paper [34] is a design of the MPC for a shell and tube heat exchanger. The designed MPC algorithm and its comparison with PID cotroller were realized only in simulation conditions. A cascade GPC for a heat exchanger process is proposed in [35]. The result of this paper is the simulation study of the effect of the cascaded GPC and basic GPC control algorithms on a model of heat exchangers. Adaptive GPC of a heat exchanger pilot plant is designed in [36]. The performance of the proposed controller is illustrated by a simulation example of a heat exchanger pilot plant.

From the above-mentioned citations it is obvious that most authors deal only with verification of the designed MPC algorithms by simulation and no by real-time control of real heat exchangers. It is also necessary to consider different structures of the individual equipments. Therefore a comparison of real-time control-loops is very problematic.

7 Conclusion

The contribution presents the adaptive predictive control applied to the time-delay process – the laboratory heat exchanger. The predictive controller is based on the recursive computation of predictions by direct use of the CARIMA model. The computation of predictions was extended for time-delay systems. A linear model with constant coefficients used in pure model predictive control can not describe the control system in all its modes. Therefore, an adaptive approach was applied. It consists of the recursive identification and the predictive controller. The model parameter estimates obtained from the identification procedure are used in the adaptive predictive controller. The GPC based on a minimisation of the quadratic criterion was derived and tested. For obtaining of a suitable model for simulation verification were used the experimental data measured on the laboratory heat exchanger system. This laboratory equipment was identified by combination of various input signals. Two off-line identification methods were used. The parameter estimates of one suitable discrete model from the point of view of quality identification were used in the initial part of the real-time control (the use *a priori* information). The designed adaptive GPC method was verified also in the case without *a priori* information. The real-time experiments confirmed that the predictive approach is able to cope with the given control problem. The real-time experiments demonstrated that the outdoor temperature has great influence up to dynamical behaviour of the laboratory heat exchanger. The following research will be directed to the extension of the designed predictive algorithm over the measurable disturbance.

Conclusion Remark:

This paper was included in the Special Issue on Multi-Models for Complex Technological Systems [37]. The Special Issues of the WSEAS Transactions on Systems [37] – [51] are very useful means for publication of monotematically focused contributions into an above mentioned journal. The Special Issues enable faster and easier access of interested academics and researches for the acquisition of partial necessary information in their research area.

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