DECOUPLING PREDICTIVE CONTROL BY ERROR DEPENDENT TUNING OF THE WEIGHTING FACTORS

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Abstract
Some decoupling techniques are presented for TITO processes. By the first method the reference signal change is decelerated in order to make the control slower and to reduce the coupling effect. A new filter design is recommended for calculating the modified reference signal which suppresses the effect of the disturbance in the other control variable whose set-point was kept constant. In the second method different control error weighting factors are used for the two controlled outputs. The adoption of the weighting factors has to be synchronized to the reference signal change. A new automatic adoption procedure is introduced which makes the synchronisation superfluous by setting the weighting factor dependent on the control error.

Keywords: Multivariable control, predictive control, decoupling, controller tuning.

Introduction

Decoupling is very important with MIMO (Multi-Input, Multi-Output) processes. One of the advantages of predictive control is that in principle no decoupling compensator has to be designed and a decision about the best input-output pairing is superfluous. On the other side the decoupling is perfect only if the control increments are not weighted which may result in non-smooth control. Therefore a practical method for decoupling is required.

Maurath, Seborg and Mellichamp (1986) considered the predictive control of a TITO (Two Input, Two Output) process for set-point change only in one controlled variable while the other set-point is kept constant. The control aim is a relatively fast control in case of set-point change while minimizing the control error of the other variable, i.e. minimizing the coupling effect. In their paper three methods are recommended:

1. Constrained control:

The controlled variable whose set-point was not changed is limited within a small range around its set-point, i.e. the control error of this variable is limited. The disadvantage is that the multivariable control algorithm has to be applied under constraints.

2. Using a decelerated set-point change:

A slower change of the reference signal leads to less coupling effect. The stepwise change of the set-value can be replaced by a modified reference signal equal to the controlled variable of the decoupled case.

3. Different weighting factors of the control errors:

The weighting factor of the control error of the variable whose set-point was not changed should be increased against that controlled variable whose set-point was changed. The advantage of the method is that the control algorithm can be designed and performed without any constraints. It is disadvantageous, however, that the time point of the weighting factor change has to be synchronized to the change in the reference signal which fact requires a simple "signal detector".

Among the three methods the change of the weighting factors can be realized most easily. The question is whether the timing of the change of the weighting factor can be realized practically by synchronization to the set-point changes using a "set-point change detector". An easy solution to this problem is setting the weighting factors as functions of the control error. With a stepwise change of the reference signal of a controlled variable the control error increases faster than the control error of the other variable whose set-point was kept constant. Consequently, if the weighting factor is set inverse proportional to the control error for both controlled variables then after a stepwise change of a reference signal the weighting factor of the output whose set-point was not changed will be higher than the weighting factor of the output whose set-point was changed.

The new tuning procedure of the weighting factors works automatically, thus no extra synchronisation is necessary. After the illustration of the method for a TITO process the procedure is simulated with the distillation and bottom product concentration control of a column.

1. The Control algorithm

The cost function of a TITO predictive control is

$$J=\lambda_{y1}\sum_{n_e=n_{e11}}^{n_{e12}}[y_{r1}^*(k+d_1+1+n_e)-\hat{y}_1(k+d_1+1+n_e\,|\,k)]^2$$

$$+\lambda_{y2}\sum_{n_e=n_{e12}}^{n_{e22}}[y_{r2}^*(k+d_2+1+n_e)-\hat{y}_2(k+d_2+1+n_e\,|\,k)]^2$$

$$+\lambda_{u1}\sum_{j=1}^{n_{u2}}\Delta u_1^2(k+j-1)+\lambda_{u2}\sum_{j=1}^{n_{u2}}\Delta u_2^2(k+j-1)\Rightarrow \underset{\Delta\mathbf{u}(k)}{MIN} \qquad (1)$$

with the denotations:

- d_i: discrete (physical) dead time relative to the sampling time of the i-th output,
- $y_{ri}(k+d_i+1+n_{ei}\,|\,k)$ reference signal of the i-th output n_{ei} steps over the dead time d_i,
- $y_{ri}^*(k+d_i+1+n_{ei}\,|\,k)$ modified reference trajectory of the i-th output n_{ei} steps over the dead time d_i,
- $\hat{y}_i(k+d_i+1+n_{ei}\,|\,k)$ predicted i-th output signal n_{ei} steps over the dead time d_i.

The modified reference trajectory can be equal to the reference signal. Often it is a filtered one, in order to decelerate stepwise changes and to smooth the control behavior.

The tuning parameters of the control algorithm are:

- $n_{e2i}-n_{e1i}+1$: the length of the prediction horizon for the i-th output
- n_{ui}: the length of the control horizon of the i-th input (the number of the supposed consecutive changes in the control signal),
- λ_{y1}, λ_{y2}: weighting factors of the control error of the i-th output,
- λ_{u1}, λ_{u2}: weighting factors of the control increments of the i-th input,

$$\Delta\mathbf{u}(k)=[\Delta u_1(k\,|\,k),\Delta u_1(k+1\,|\,k),\ldots,\Delta u_1(k+n_{u1}-1\,|\,k),\\ \Delta u_2(k\,|\,k),\Delta u_2(k+1\,|\,k),\ldots,\Delta u_2(k+n_{u2}-1\,|\,k)]^T \qquad (2)$$

are the actual control increments, which have to be optimized.

Define the vectors for the i-th output in the future time domain $k+d_i+n_{e1i}\le j\le k+d_i+n_{e2i}$

of the reference signal sequence

$$\mathbf{y}_{ri}=[y_{ri}(k+d_i+1+n_{e1i}\,|\,k),\ldots,y_{ri}(k+d_i+1+n_{e2i}\,|\,k)]^T$$

and of the predicted signal sequence

$$\hat{\mathbf{y}}_i=[\hat{y}_i(k+d_i+1+n_{ei1}\,|\,k),\ldots,\hat{y}_i(k+d_i+1+n_{ei2}\,|\,k)]^T$$

The predicted output signal can be splitted into free and forced responses

$$\hat{\mathbf{y}}_i=\hat{\mathbf{y}}_{i,\,forc}+\hat{\mathbf{y}}_{i,\,free}$$

where the predicted forced i-th output can be expressed as

$$\hat{\mathbf{y}}_{i,\,forc}=\sum_{j=1}^{M}\mathbf{H}_{ji}\Delta\mathbf{u}_j$$

with the unknown control sequence in the control horizon

$$\Delta\mathbf{u}_j=[\Delta u_j(k\,|\,k)\quad \Delta u_j(k+1\,|\,k)\quad\cdots\quad \Delta u_j(k+n_{uj}-1\,|\,k)\,]^T$$

and a matrix of step response coefficients of the process model

$$\mathbf{H}_{ji}=\begin{bmatrix} h_{ji}(n_{e1i}+1) & h_{ji}(n_{e1i}) & \cdots & h_{ji}(n_{e1i}-n_{uj}+2)\\ h_{ji}(n_{e1i}+2) & h_{ji}(n_{e1i}+1) & \cdots & h_{ji}(n_{e1i}-n_{uj}-1)\\ \vdots & \vdots & \vdots & \vdots\\ \vdots & \vdots & \vdots & \vdots\\ h_{ji}(n_{e2i}+1) & h_{ji}(n_{e2i}) & \cdots & h_{ji}(n_{e2i}-n_{uj}+2)\end{bmatrix}$$

where

$$h_{ji}(k)=0;\quad \text{if}\quad k<0;\quad \forall i,\forall j$$

For a TITO process define the following vectors of signal sequences in the prediction time domain $k+d_i+n_{e1i}\le j\le k+d_i+n_{e2i}$:

- $\mathbf{y}_r^*=\left[y_{r1}^{*T},y_{r2}^{*T}\right]^T$: modified reference signal,
- $\hat{\mathbf{y}}=[\hat{y}_1^T,\hat{y}_2^T]^T$: predicted outputs,
- $\hat{\mathbf{y}}_{forc}=[\hat{y}_{1\,forc}^T,\hat{y}_{2\,forc}^T]^T$: predicted forced outputs,
- $\hat{\mathbf{y}}_{free}=[\hat{y}_{1\,free}^T,\hat{y}_{2\,free}^T]^T$: free responses

and

$\Delta\mathbf{u}=[\Delta\mathbf{u}_1^T,\Delta\mathbf{u}_2^T]^T$: vector of all control input signals in the control horizon $k\le j\le k+n_{ui}-1$

Now the predicted forced i-th output can be calculated as

$$\hat{\mathbf{y}}_{i,\,forced}=\sum_{j=1}^{2}\mathbf{H}_{ji}\Delta\mathbf{u}_j=\mathbf{H}_i\Delta\mathbf{u}$$

where

$$\mathbf{H}_i=[\mathbf{H}_{1i},\mathbf{H}_{2i}]^T$$

The vector of the predicted outputs is the sum of the predicted forced and free responses:

$$\hat{\mathbf{y}}=\hat{\mathbf{y}}_{forced}+\hat{\mathbf{y}}_{free},$$

with

$$\hat{\mathbf{y}}_{forced}=\begin{bmatrix}\mathbf{H}_1\\ \mathbf{H}_2\end{bmatrix}\Delta\mathbf{u}=\mathbf{H}\Delta\mathbf{u}$$

The cost function becomes

$$J=\left(\mathbf{y}_r^*-\hat{\mathbf{y}}\right)^T\mathbf{\Lambda}_y\left(\mathbf{y}_r^*-\hat{\mathbf{y}}\right)+\Delta\mathbf{u}^T\mathbf{\Lambda}_u\Delta\mathbf{u}\Rightarrow \underset{\Delta\mathbf{u}(k)}{MIN}$$

with the weighting matrix of the control errors

$$\mathbf{\Lambda}_y=\mathbf{diag}\left\langle\mathbf{\Lambda}_{y1},\mathbf{\Lambda}_{y2}\right\rangle$$

Substituting the vector of forced and free responses results in

$$J = \left(\mathbf{y}_r^* - \mathbf{H}\Delta\mathbf{u} - \hat{\mathbf{y}}_{free}\right)^T \mathbf{\Lambda}_y \left(\mathbf{y}_r^* - \mathbf{H}\Delta\mathbf{u} - \hat{\mathbf{y}}_{free}\right) + \Delta\mathbf{u}^T \mathbf{\Lambda}_u \Delta\mathbf{u} \Rightarrow \underset{\Delta\mathbf{u}(k)}{MIN}$$

Unconstrained minimization of the cost function according to the whole sequence of input increments in the control time domain leads to

$$\frac{dJ(\Delta\mathbf{u})}{d\Delta\mathbf{u}} = -\mathbf{H}^T\left[\mathbf{\Lambda}_y^T + \mathbf{\Lambda}_y\right]\left(\mathbf{y}_r^* - \mathbf{H}\Delta\mathbf{u} - \hat{\mathbf{y}}_{free}\right) + \left[\mathbf{\Lambda}_u^T + \mathbf{\Lambda}_u\right]\Delta\mathbf{u} = \mathbf{0}$$

which results in

$$\Delta\mathbf{u} = \begin{bmatrix} \mathbf{H}^T\left(\mathbf{\Lambda}_y^T + \mathbf{\Lambda}_y\right)\mathbf{H} \\ + \left(\mathbf{\Lambda}_u^T + \mathbf{\Lambda}_u\right) \end{bmatrix}^{-1} \mathbf{H}^T\left(\mathbf{\Lambda}_y^T + \mathbf{\Lambda}_y\right)\left(\mathbf{y}_r^* - \hat{\mathbf{y}}_{free}\right)$$

All weighting matrices (and all sub-weighting matrices) are diagonal, since the control error and the control effort (increment) are considered as square functions of the same time point and no cross-products exist between different time points

$$\mathbf{\Lambda}_{yi} = \lambda_{yi}\mathbf{I} \quad \text{and} \quad \mathbf{\Lambda}_{ui} = \lambda_{ui}\mathbf{I}$$

where $\mathbf{I}$ is the identity matrix. As with diagonal matrices the transposed matrix is equal to the non-transposed one

$$\mathbf{\Lambda}_y^T = \mathbf{\Lambda}_y \quad \text{and} \quad \mathbf{\Lambda}_u^T = \mathbf{\Lambda}_u$$

then

$$\Delta\mathbf{u} = \left[\mathbf{H}^T\mathbf{\Lambda}_y\mathbf{H} + \mathbf{\Lambda}_u\right]^{-1}\mathbf{H}^T\mathbf{\Lambda}_y\left(\mathbf{y}_r^* - \hat{\mathbf{y}}_{free}\right)$$

According to the receding horizon technique only the actual control signals will be used and the computation is repeated in the next control step. Denote the actual control increments by

$$\Delta\mathbf{u}_{actual}(k) = [\Delta u_1(k), \Delta u_2(k)]^T,$$

which are part of the whole control increment vector (Eq. (2)) and they can be expressed as

$$\Delta\mathbf{u}_{actual}(k) = [1,0,...,0,\ 1,0,...,0\ ]^T \Delta\mathbf{u}(k)$$

where the number of zeros are n_{u1}-1 and n_{u2}-1 respectively.

2. Control without and with ideal decoupling

In order to illustrate the problem of coupling a TITO process model (Fig. 1) was considered.

During control the two output variables (y_1, y_2) of the process become the controlled variables (CV) and the two input variables (u_1, u_2) are the manipulated variables (MV).

The sub-models are aperiodic processes with different static gain K_{pij}, time constants T_{ij}, and dead time T_{di}. All processes have some (n_{ij}) equal time constants:

- P_{11}: K_{p11}=1.5, T_{11}=1.0 min, n_{11}=2, T_{d11}=0.1 min
- P_{12}: K_{p12}=0.5, T_{12}=0.5 min, n_{12}=4, T_{d12}=0.5 min
- P_{21}: K_{p21}=0.75, T_{21}=0.5 min, n_{21}=3, T_{d21}=0.8 min
- P_{22}: K_{p22}=1.0, T_{22}=2.0 min, n_{22}=1, T_{d22}=0.2 min

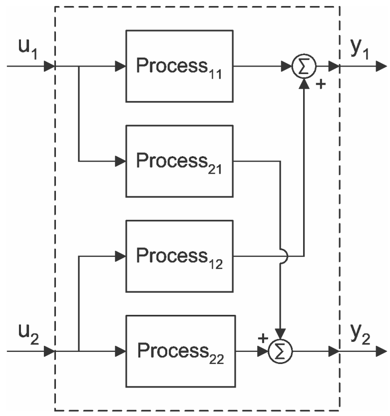

Fig. 1. TITO process model

Fig. 2 shows the unit step responses of the sub-models.

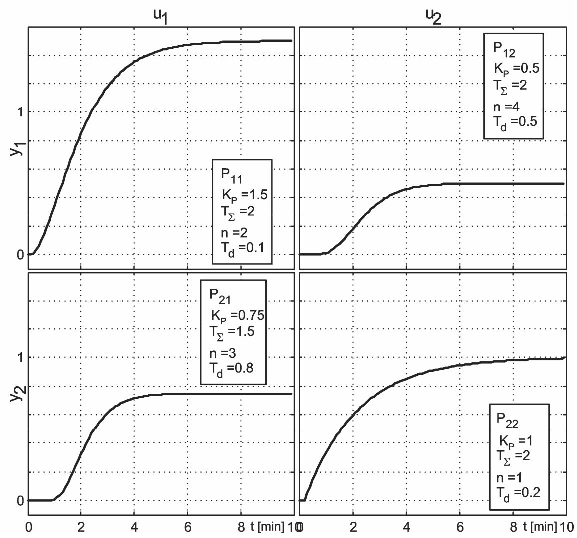

Fig. 2. Sub-models of the TITO process: outputs y_i to input unit steps in u_i (top left:P_{11}, top right:P_{12}, bottom left:P_{21}, bottom right:P_{22},

Fig. 3 shows the TITO predictive control without decoupling. The sampling time was ΔT=0.1 min and the controller parameters are:

- start of control error horizons: $n_{e11}=n_{e12}$=0,
- end of control error horizons: $n_{e21}=n_{e22}$=90,
- length of control horizons: $n_{u1}=n_{u2}$=30,
- weighting factors of the control errors $\lambda_1=\lambda_2$=1,
- weighting factors of the control increments $\lambda_{u1}=\lambda_{u2}$=0.5.

The control scenario was:

- at t=1 min stepwise increase of the reference signal of CV1 by 1,
- at t=10 min stepwise increase of the reference signal of CV2.

In the further examples the same control scenario is always simulated with the nominal controller parameters given above except those stated extra.

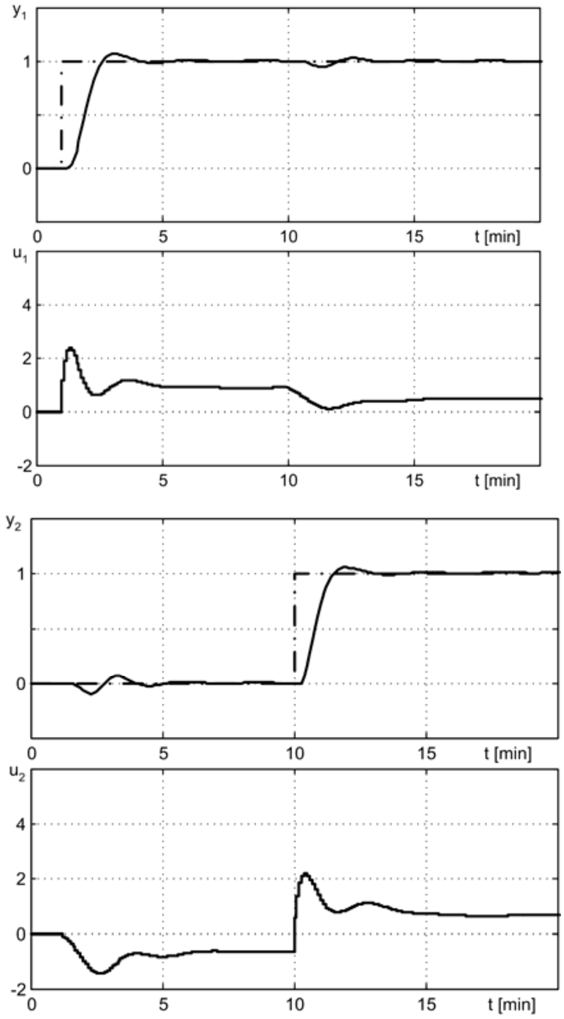

Fig. 3. TITO control without decoupling: (top: CV1, bottom: CV2)

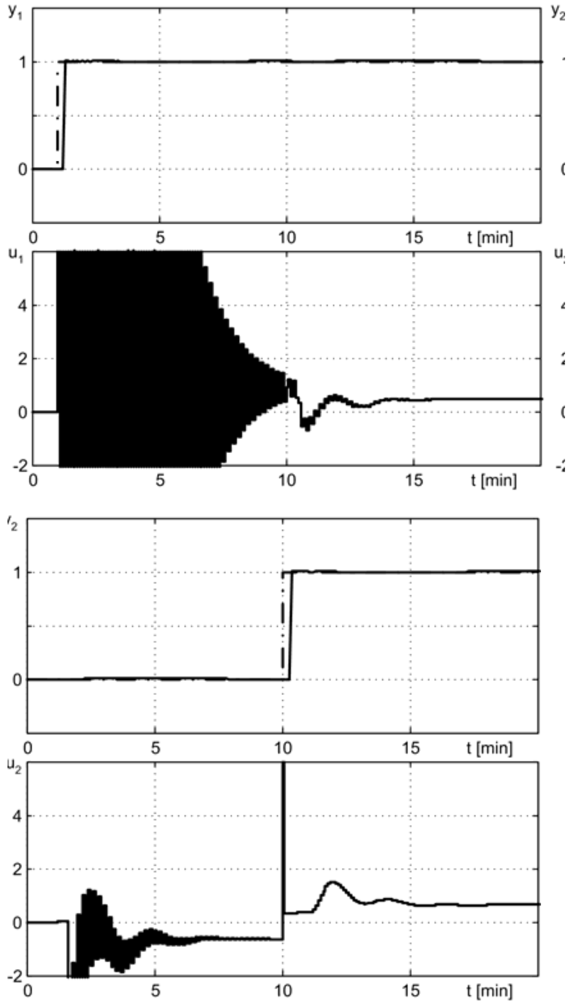

Fig. 4. TITO control with perfect decoupling without penalizing control increments (top: CV1, bottom: CV2)

The control of the set-value changes is fast with an overshoot of about 10 %. There are changes of about 10 to 15 % (related to the set-value changes) in the controlled variables whose set-value was kept constant.

A perfect decoupling can be achieved if the increments in the manipulated variables are not penalized, i.e. $\lambda_{u1}=\lambda_{u2}=0$. Fig. 4 shows the control with these controller parameters. The other tuning parameters are the same as in the case of Fig. 3.

A change in the set-value does not cause any change in the other control variable at the cost of a very drastic change in the manipulated variables. Thus this decoupling method is not practical.

3. Decoupling by decelerating the reference signal change

It is expected that a slower change of the reference signal leads to less coupling effect. This is illustrated by Fig. 5 where the stepwise change of both set-values was filtered by a first-order filter with the time constant of T_{r1}=1.5min and T_{r2}=1min. The filter parameters were selected in such a way that the filtered reference signal approximates the controlled signal without decoupling (Fig. 2).

As it is seen, any set-point change practically does not disturb the other controlled variable whose value should be remained unchanged.

In the next simulation the stepwise change of the set-value is replaced by a modified reference signal equal to the controlled variable of the decoupled case (Fig. 5) as recommended by Maurath, Seborg and Mellichamp (1986). (The remaining small coupling effects - prior and after the reference step - the dead time and the very small oscillations after the control step have been removed from the old controlled signal of Fig. 5 for the new reference signal.)

Fig. 6 demonstrates the conditioning of the reference signal. It is forced to 0 before the set-point step and is forced to 1 after the settling time. Fig. 7 shows the control using the new reference signal both for small $\lambda_{u1}=\lambda_{u2}=1$ and a higher $\lambda_{u1}=\lambda_{u2}=100$ weighting factors of the control errors. The weighting factors have to be raised because now the reference signal is not a step but a slower signal.

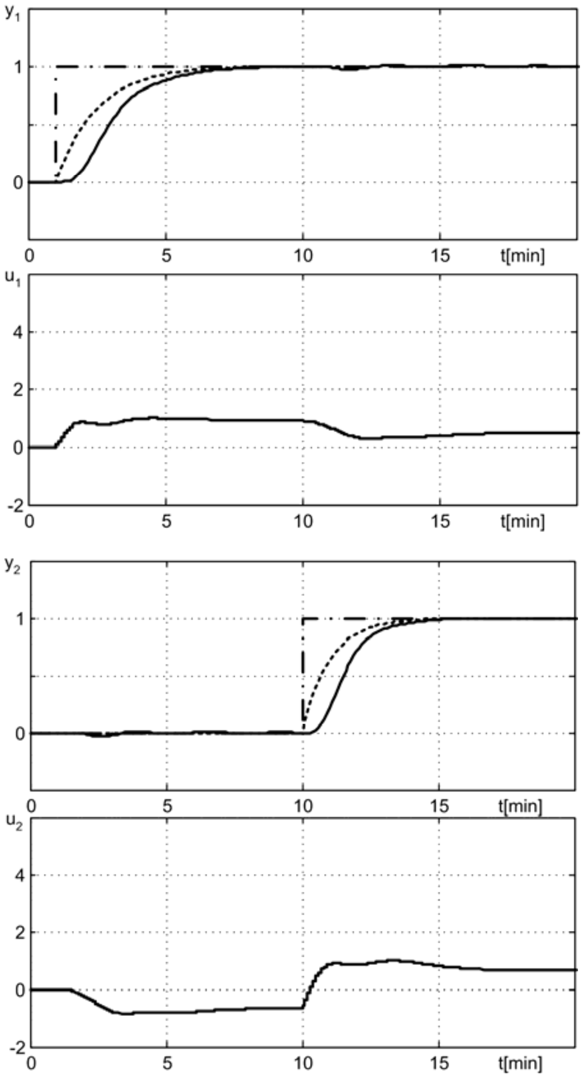

Fig. 5. TITO control with reference signal filter (top: CV1, bottom: CV2; dashed: filtered reference signal)

Instead of storing the controlled variable as a modified reference signal the actual reference signal can be filtered in such a way that the filtered reference signal would approximate the controlled signal in the decoupled case (achieved e.g. by slowing the reference signal before). This can be achieved if a filter is identified between the stepwise reference signal change and the controlled variable in the decoupled case (Fig. 5) using a conventional LS-algorithm. A filter with order 3 was required to have a sufficient fit between the reference signal change and the corresponding controlled variable. The estimated filters are:

$$y_{r1}^{F}(k) = \frac{0.0082 + 0.001055q^{-1} - 0.01332q^{-2}}{1 - 2.667q^{-1} + 2.423q^{-2} - 0.7405q^{-3}} y_{r1}(k)$$

$$y_{r2}^{F}(k) = \frac{2.308 \cdot 10^{-6} + 0.05613q^{-1} - 0.05421q^{-2}}{1 - 2.617q^{-1} + 2.304q^{-2} - 0.6843q^{-3}} y_{r2}(k)$$

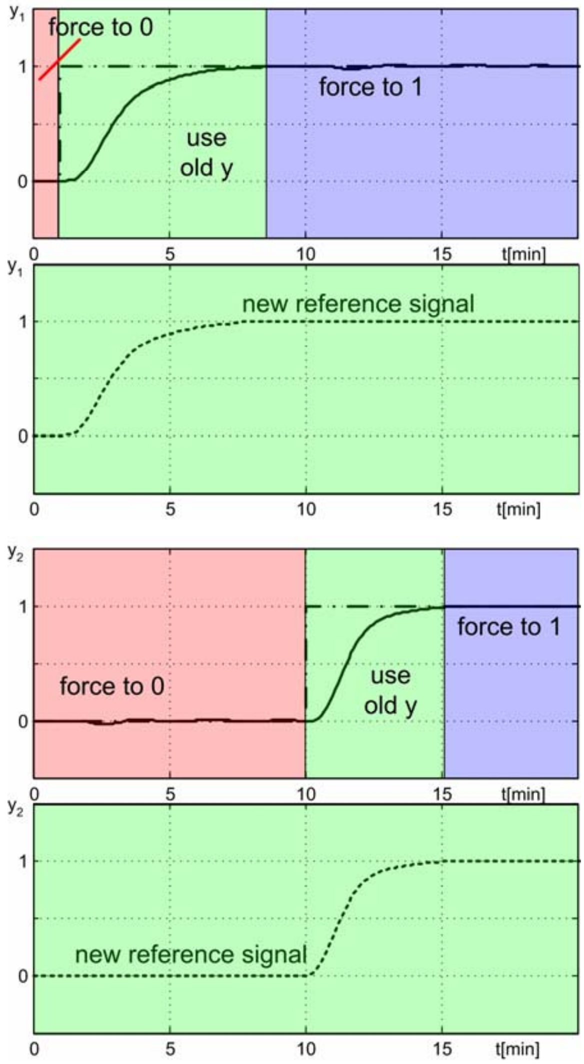

Fig. 6. Conditioning of the control signal for the TITO control with the reference signal equal to the controlled signal in the decoupled case (top: CV1, bottom: CV2; solid: controlled signal, dashed: modified reference trajectory)

This control is seen in Fig. 8. There is practically no difference whether the controlled signal from the decoupled case (achieved e.g. by slowing the reference signal before) or the filtered one was applied as a modified reference trajectory. However, the second case can be applied much easier because only some filter parameters and not a whole reference trajectory have to be stored.

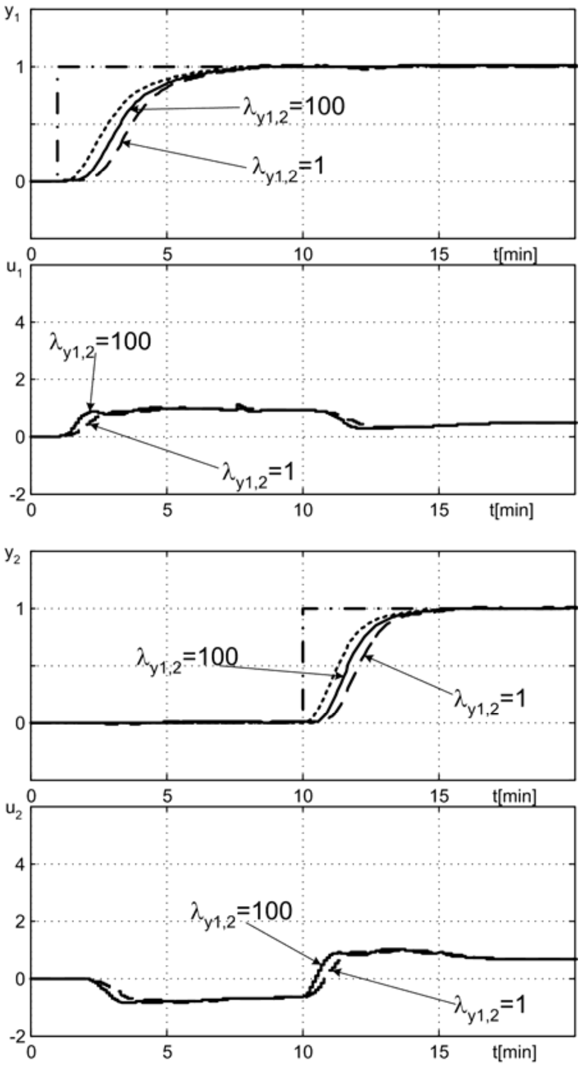

Fig. 7. TITO control with the reference signal equal to the controlled signal in the decoupled case (Fig. 5) (top: CV1, bottom: CV2; dashed: modified reference trajectory)

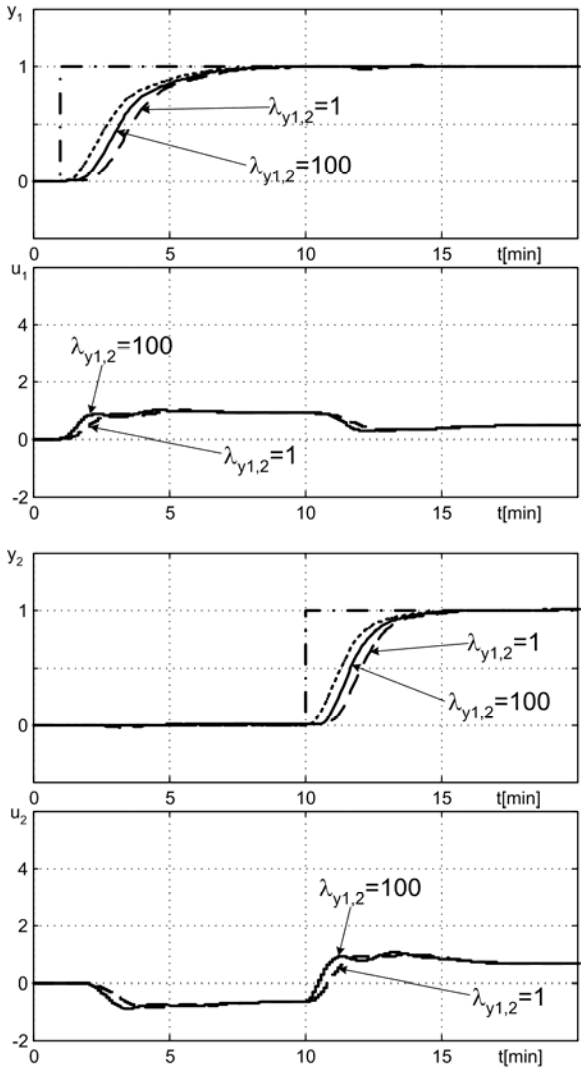

Fig. 8. TITO control with the optimally filtered reference signal (top: CV1, bottom: CV2; dashed: modified reference trajectory)

4. Weighting factor adjusting at reference signal change

As mentioned already in the introduction increasing of the control error weighting factor of the variable whose set-point was kept constant reduces the control error in this variable. Fig. 9 illustrates this case for set point changes. The weighting factors of both control errors were changed from $\lambda_{y1}=\lambda_{y2}=1$ to $\lambda_{y1}=\lambda_{y2}=100$ for that variable whose set-point was not changed in the moment of the set-point change. The duration of the change was 5 min which is a bit (about 2 min) longer than the settling time of the controlled process. The plots show that the two processes are completely decoupled.

The critical point of this method is the detection of the set-point change. In case of predictive control there are applications where the reference signal trajectories are given, so the changes in the reference signals are known in advance and stored.

If the changes in the reference signals are not known a priori, there are several methods for detecting signal changes. However, we recommend in the next section an alternative method, which does not require any signal change detector or observer.

We increased the weighting factor in the case of Fig. 9 manually and kept its value constant at least for the duration of the settling time of the closed loop controlled process. After that the weighting factor is decreased to its old value (before the set-point change) abruptly.

Bego, Peric and Petrovic (2000) applied a similar technique and decreased the weighting factor exponentially to its old value before the set-point change. They showed the effect of the choice of the starting value and the time constant of the exponential decrease, however, the parameters were tuned based on repeated simulations instead of any tuning rules. Fig. 10 shows two alternative procedures: constant or decreasing weighting factor during the settling time after the set-point change in the other controlled variable. The exponential decrease ensures a smoother change of the weighting factor and should, therefore, be preferred against an abrupt change.

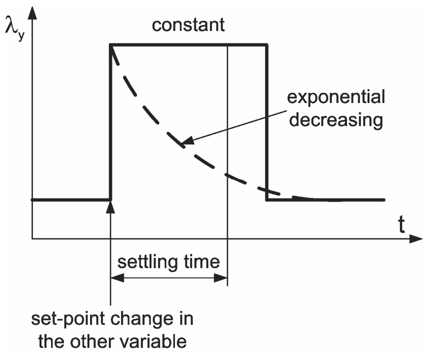

Fig. 10. Weighting factor modification strategies

5. Control error dependent weighting factor adjusting

The synchronisation at the set-value change can be performed automatically if the weighting factors are decentralized functions of the control errors. With a stepwise change of the reference signal of a controlled variable the control error increases faster than the control error of the other variable whose set-point was kept constant. Consequently, if the weighting factor is set inverse proportional to the control error for both controlled variables then after a stepwise change of a reference signal the weighting factor of the output whose set-point was not changed will be higher than the weighting factor of the output whose set-point was changed.

After some simulation trials the following dependence of the control error weighting factors on the control error seemed to be optimal:

$$\lambda_{yi} = \frac{\lambda_{yi,\max}}{\left(1 + \left|e_i(k)\right| \cdot \lambda_{yi,damp}\right)} \qquad (3)$$

with $\lambda_{y1,\max}$=10, $\lambda_{y2,\max}$=20, $\lambda_{y1,\mathrm{damp}}$=100 and $\lambda_{y2,\mathrm{damp}}$=100.

The control is slightly slower than with the manual adaptation of the control error weighting (Fig. 9) but the control is still fast and the decoupling is very good (as before). The automatic adaptation of the control error weighting shows also a decrease of the other controlled signal whose set-value was kept constant which is an indicator of the remaining coupling effects. But these effects are very small and thus also the decrease of the control error weighting is small. From Fig. 11 one can see that the weighting factors of those controlled variable whose set-value was stepwise changed were temporarily significantly reduced. It has to be mentioned that the change of the λ_{y1} and λ_{y2} weighting factors approximates an exponential course (similar to Fig. 10). (Remember that an exponential change of the weighting factors is preferred over a stepwise change.)

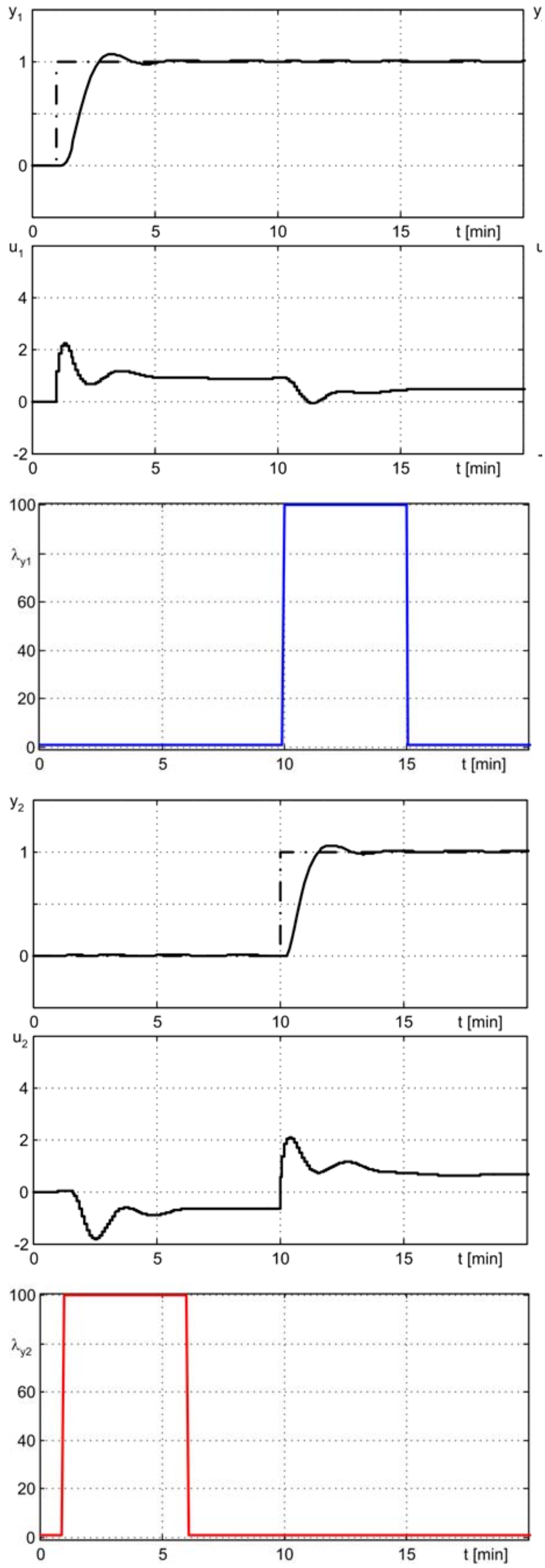

Fig. 9. TITO control with the weighting factor change at set-point steps (top: CV1, MV1, λ_{y1}, bottom: CV2, MV1, λ_{y2})

6. Application to a distillation column model

Fig. 12 shows a typical column used for separating chemical petrol:

- feed: chemical petrol from the desulfurisation,
- top product: light petrol,
- bottom product: heavy petrol.

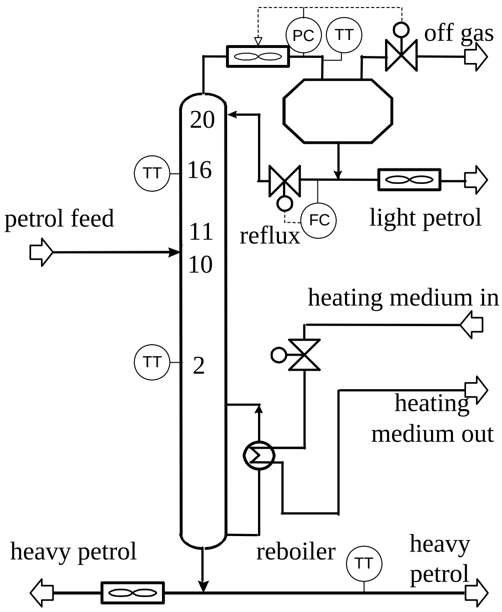

Fig. 12 Piping and instrumentation scheme of the distillation column

Fig. 13 shows the process model between the variables

- <u>manipulated variables</u>:
  - reflux flow,
  - heating power (duty),
- <u>controlled variables</u>:
  - (pressure compensated) top temperature,
  - (pressure compensated) bottom temperature.

All times are given in the transfer functions in minutes.

In the following simulation plots the following ranges of the variables were scaled to 0 to 100 %: (pressure compensated) top temperature (TOP-PCT) 50 to 64 °C, (pressure compensated) bottom temperature (BOT-PCT) 148 to 162 °C, reflux flow -200 to 520 ton's per day and heating power (duty) 3 to 10 MW. At time t=10 min the set point of the top temperature was decreased by 3°C and at time t=200 min the set point of the bottom temperature was increased changed by 2°C.

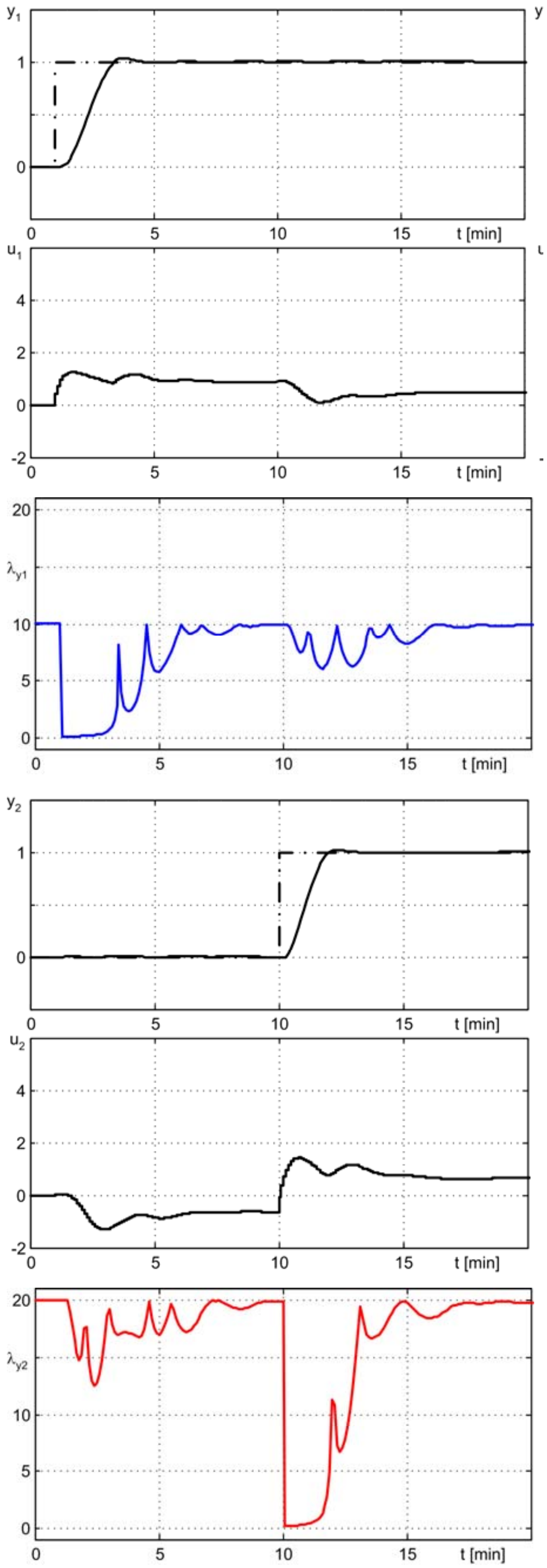

Fig. 11. TITO control with error-dependent weighting factors (top: CV1, MV1, λ_{y1}, bottom: CV2, MV1, λ_{y2})

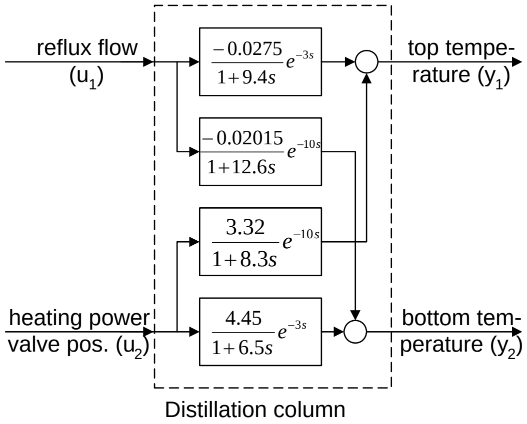

Fig. 13 TITO process model of the distillation column

The multivariable control was simulated without any constraints and with the sampling time ΔT=1 min, control error prediction horizon of $n_{e11}=n_{e12}=0$ and $n_{e21}=n_{e22}=100$, manipulated variable horizon $n_{u1}= n_{u2}=25$, weighting of the control error and of the control increments for the first and second manipulated variables $\lambda_{y1}=\lambda_{y2}=1$, $\lambda_{u1}=0.03412^2$ and $\lambda_{u2}=5{,}5522^2$, respectively, as shown in Fig. 14.

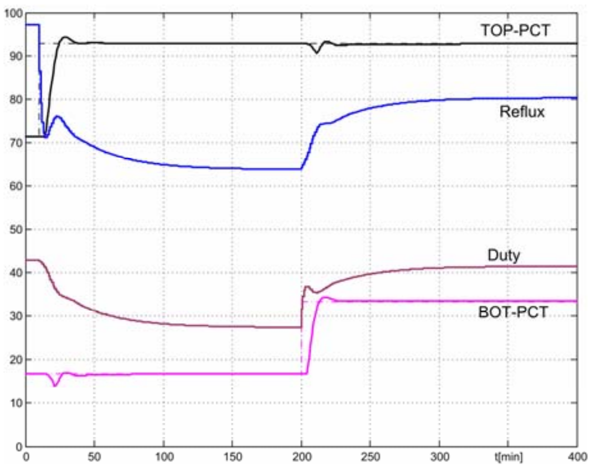

Fig. 14 Control of the TITO distillation column model with constant control error weighting factors (CV1: TOP-PCT, CV2: BOT-PCT, MV1: Reflux and MV2: Duty)

One can see that the set-point change disturbs the other variable, which should be remained constant. This coupling effect can be suppressed by changing the control error weighting factor as a function of the control error as explained before.

A good decoupling could be achieved by the same dependence of the weighting factors as in Eq. 3 with $\lambda_{y1,max}=1$, $\lambda_{y2,max}=1$, $\lambda_{y1,damp}=25$ and $\lambda_{y2,damp}=25$. Fig. 15 shows the practically decoupled control.

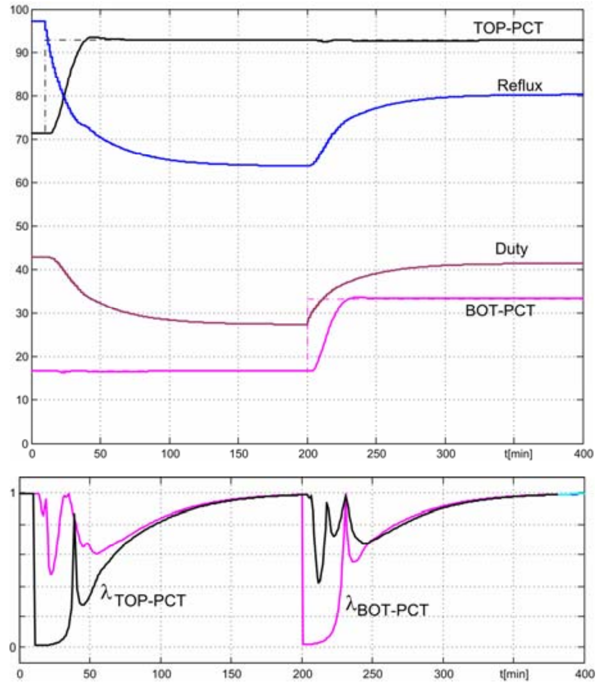

Fig. 15 Control of the TITO distillation column model with control error dependent control error weighting factors (top: CV1: TOP-PCT, CV2: BOT-PCT, MV1: Reflux and MV2: Duty; bottom: $\lambda_{TOP\text{-}PCT}$, $\lambda_{BOT\text{-}PCT}$

7. Conclusion

Several decoupling methods were presented for TITO processes.

By the first method the actual reference signal was substituted by a modified, decelerated reference signal in order to damp the disturbance caused in the other variable whose set-point was not changed. As an optimal modified reference signal the controlled signal in the decoupled case (achieved by slowing the reference signal before) was used. Instead of storing the whole reference trajectory a new method was recommended by identifying a reference signal filter and filtering the actual reference signal by it.

By the second method the control error weighting factor of that variable, whose set-value was not changed is increased in order to suppress the decoupling effect. Instead of synchronizing this adoption to the set-point change by using a signal detector the weighting factor was set as a function of the control error. By doing this an automatic adoption was possible.

Several simulations demonstrate the proper functioning of the proposed methods. The automatic adoption method is illustrated with the TITO model of a distillation column. While controlling the concentration of the distillation and the bottom product the usual coupling effect could be suppressed by a proper choice of the weighting factor adoption.

The procedures presented for TITO processes can be easily extended for MIMO systems of high dimensionality.

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