TWO-DEGREE-OF-FREEDOM MULTIRATE CONTROLLERS FOR NONLINEAR PROCESSES

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Abstract: This work focuses on developing nonlinear multirate model algorithmic controllers for nonlinear processes using a closed-loop observer. Conditions for the observer function and a gain corrector function, which is necessary to ensure that the resulting control structure has integral action, are given. The control action is calculated using the corrected states. The resulting structure is a two-degree-of-freedom multirate controller. The performance of the proposed method is evaluated through simulation of a chemical process.

Keywords: nonlinear control, multirate, decoupling, multivariable control, process control

1. INTRODUCTION

Many industrial processes have measurements that are available at different rates. Temperatures, pressure, and flow rates can typically be measured with a short sampling interval. Compositions and product properties usually cannot be made available as rapidly. In the continued drive to operate chemical processes more efficiently and effectively, increasing demands are put on automated process control algorithms to make the best use of measurements made at different rates, as well as compensate for the inherent nonlinearities the systems possess. Both linear and nonlinear Model Predictive Control approaches have been proposed for multirate systems (Lee, et al, 1992, Ohshima, et al, 1994, Bequette, 1991). More recently, an approach based on Model Algorithmic Control (MAC) methods (Richalet, et al, 1978, Mehra and Rouhani, 1980, Soroush and Kravaris, 1996) was proposed for nonlinear multirate processes (Niemiec and Kravaris, 2002). Like the general MAC formulations, this work used an open-loop observer for estimates of the process states.

Methods developed recently for nonlinear single rate processes have made use of a closed-loop observer in a model-state feedback structure (Wright and Kravaris, 2000, Wright and Kravaris 2001). This extends the class of systems to which the method is applicable as well as providing an improved set of state estimates. The goal of the present work is to derive a nonlinear multirate Model Algorithmic Control structure along the lines of Niemiec and Kravaris (2002), but using the closed-loop observer as in Wright and Kravaris (2001). The resulting control algorithm is a two-degree-of-freedom control law, in the sense that the control action is not a function of the error only, but the output and set point are processed in different ways. Once developed, the proposed method will be applied to a chemical reactor system and its performance will be evaluated by simulation.

2. SYSTEM DESCRIPTION AND ASSUMPTIONS

Consider the nonlinear discrete-time MIMO system represented by:

$$\mathbf{x}(k+1) = \Phi(\mathbf{x}(k),\mathbf{u}(k)) \qquad (1)$$
$$\mathbf{y}(k) = h(\mathbf{x}(k))$$

where Φ:Â^n^xÂ^m^→Â^n^, h: Â^n^→Â^m^ are smooth functions, $\mathbf{x} \in$ Â^n^ is the system state, $\mathbf{u} \in$ Â^m^ are the system inputs, and $\mathbf{y} \in$ Â^m^ are the system outputs. It is assumed that the system has locally well-defined steady-state characteristics, and the relative orders of the m controlled outputs, $r_1, \ldots, r_m$, are all finite.

With each time $k\Delta t$, where k is an integer and Δt is the time step of the model, the manipulated inputs are actuated. Of the m outputs, q are considered fast, $\mathbf{y}_f^I \in \Re^q$, meaning that they are sampled at every time instant. The remaining p = m – q outputs are considered slow, $\mathbf{y}_s^I \in \Re^p$, meaning they are sampled regularly but at a rate slower than every time instant. For each time that is a multiple of $N_i\Delta t$, where N_i is an integer constant, the output measurement $\mathbf{y}_{si}^I$ is received. N_i is defined as the ratio of the ith output sampling period to the input actuation period:

$$N_i = \frac{\text{sampling period of the input i}}{\text{period of input actuation}} \qquad (2)$$

In addition, there may be ℓ secondary outputs, $\mathbf{y}_f^{II} \in \Re^\ell$, (where $\ell \geq 0$) which are sampled at every time instant. There are no slow secondary outputs.

3. NONLINEAR MULTIRATE MODEL-ALGORITHMIC CONTROL

A main point of departure for the current work is the nonlinear multirate model-algorithmic controller (MAC) of Niemiec and Kravaris (2002). The complete structure of the controller developed in that work is shown in Figure 1.

In this structure, the vector of model states $\mathbf{x}_M$ is obtained by simulating the process model (1) online:

$$\mathbf{x}_M(k+1) = \Phi(\mathbf{x}_M(k),\mathbf{u}(k)) \qquad (3)$$

From the process model, future changes of the outputs can be predicted. The predicted changes of the output can be added to the latest available output measurement to obtain predictions of each output. For each of the outputs, a reference trajectory can be defined according to:

$$\hat{y}_i(k+r_i) = (1-\alpha_i)y_{isp} + \alpha_i \hat{y}_i(k+r_i-1) \qquad (4)$$

where sp denotes the output set point and is a tunable scalar parameter such that $0 \leq \alpha_i < 1$. Matching the output predictions with the reference trajectories

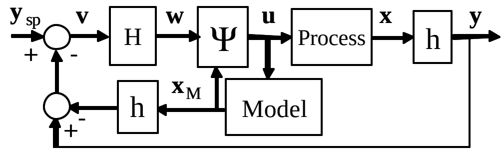

Figure 1: Structure of Nonlinear Multirate MAC

gives a set of nonlinear algebraic equations that must be solved numerically online for the input vector:

$$h_1^{r_1-1}[\Phi(\mathbf{x}_M(k),\mathbf{u}(k))] = \alpha_1 h_1^{r_1-1}[\mathbf{x}_M(k)] + (1-\alpha_1)\left[y_{1sp} - y_1\left(\left[\frac{k}{N_1}\right]N_1\right) + h_1\left[\mathbf{x}_M\left(\left[\frac{k}{N_1}\right]N_1\right)\right]\right]$$
$$\vdots \qquad (5)$$
$$h_m^{r_m-1}[\Phi(\mathbf{x}_M(k),\mathbf{u}(k))] = \alpha_m h_m^{r_m-1}[\mathbf{x}_M(k)] + (1-\alpha_m) \bullet \left[y_{msp} - y_m\left(\left[\frac{k}{N_m}\right]N_m\right) + h_m\left[\mathbf{x}_M\left(\left[\frac{k}{N_m}\right]N_m\right)\right]\right]$$

where $[k/N_i]$ denotes the integer part of k/N_i. The output measurement y_i is taken only at the time instants $[k/N_i]N_i$, but the manipulated inputs are actuated at every k. This equation utilizes the best available information, which is the most recent measurement at $[k/N_i]N_i$, to predict the future values of the slowly sampled output y_i. Using this structure, a controller can be derived that not only includes the necessary information for good control of outputs sampled at the lowest rates but also exhibits good disturbance rejection for outputs sampled at faster rates. For measurements available at a sampling period equal to the input actuation period (N_i=1), $[k/N_i]N_i$ will reduce to k in the notation.

The corresponding implicit algebraic function defined as the solution to (5) is given by

$$\mathbf{u}(k) = \Psi[\mathbf{x}_M(k), \mathbf{w}(k)] \qquad (6)$$

where Ψ[*,*] is the same function as that in the single-rate MAC controller and

$$w_i(k) = y_{isp} - y_i\left(\left[\frac{k}{N_i}\right]N_i\right) + h_i\left[\mathbf{x}_M\left(\left[\frac{k}{N_i}\right]N_i\right)\right] \qquad (7)$$

With the model states obtained by simulating (3) online, the resulting nonlinear multirate model-algorithmic controller can be expressed as:

$$\mathbf{x}_M(k+1) = \Phi(\mathbf{x}_M(k), \Psi[\mathbf{x}_M(k),\mathbf{w}(k)])$$
$$u(k) = \Psi[\mathbf{x}_M(k),\mathbf{w}(k)] \qquad (8)$$

Note that the calculation of $w_i(k)$ involves a hold operation on both $y_i(k)$ and $h[\mathbf{x}_M(k)]$:

$$w_i(k) = H\left(y_{isp} - y_i(k) + h_i[\mathbf{x}_M(k)]\right)$$
$$= y_{isp} - y_i\left(\left[\frac{k}{N_i}\right]N_i\right) + h_i\left[\mathbf{x}_M\left(\left[\frac{k}{N_i}\right]N_i\right)\right] \quad (9)$$

where H is a hold operator.

Closed-loop properties of the complete structure shown in Figure 1 are proven in Niemiec and Kravaris (2002).

4. MODEL-STATE FEEDBACK WITH CLOSED-LOOP OBSERVER

In Wright and Kravaris (2001), a model-state feedback control structure is developed for nonlinear discrete-time SISO systems using a closed-loop observer. Closed-loop observers, in general, do not preserve the steady-state gain between the manipulated inputs and process states. Incorporating only a closed-loop observer into a model-state feedback structure would result in a controller that did not possess integral action. By analogy with linear static state feedback controllers, a gain correction function is designed that restores the steady-state gain and the corrected states are used in the calculation of the manipulated input. The complete control structure is shown in Figure 2.

In this structure, the reference input v is calculated by

$$v(k) = y_{sp}(k) - y(k) + h(x_c(k)) \quad (10)$$

The manipulated inputs are calculated by a static state feedback of the form:

$$u(k) = \Psi(x_c(k), v(k)) \quad (11)$$

where Ψ:Â^{n}xÂ→Â^n, is a smooth scalar function, with the property:

$$x = \Phi(x, \Psi(x, v)) \Rightarrow h(x) = v \quad (12)$$

which insures unity steady-state gain between v and y.

In determining the closed-loop observer and gain correction functions, it is first necessary to define what will be considered an observer for a nonlinear process (where $\rho(k) = y(k) - h(\hat{x}(k))$):

Definition: (Lin and Byrnes, 1995) A dynamic system of the form

$$\hat{x}(k+1) = \Pi(\hat{x}(k), u(k), \rho(k)) \quad (13)$$

is called an observer for (1) if the function $\Pi(x,u,\rho)$: Â^{n}xÂxÂ→Â^n has the property that $\Pi(x,u,0) = \Phi(x,u)$, for all x, u

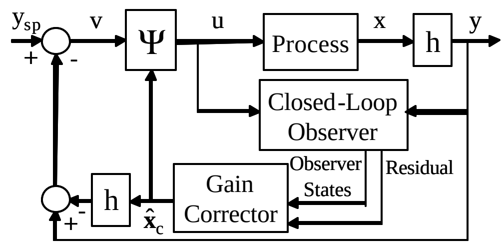

Figure 2: Model-state feedback structure with closed-loop observer

Specifications do not determine the functions $\Pi(x,u,\rho)$ and $\omega(x,\rho)$ uniquely. The Π and ω functions must satisfy the following properties:

(P1) $\Pi(x,u,0) = \Phi(x,u)$
(P2) $\Pi(x,u,\rho) = 0 \Rightarrow \Phi(\omega(x,\rho),u)=0$
(P3) the eigenvalues of $\frac{\partial\Phi}{\partial x} - \frac{\partial\Pi}{\partial\rho}\frac{\partial h}{\partial x}$ evaluated at reference conditions must assume desirable values.

A convenient functionality for the observer can be postulated which is affine in the residual with constant coefficients:

$$\Pi(x,u,\rho) = \Phi(x,u) + L\rho \quad (14)$$

This automatically satisfies property (P1). It is straightforward to show that the adjustable parameters L can be easily selected to satisfy (P3). The challenge is to find the ω-function to satisfy property (P2), which, for the above choice of the observer, becomes

$$\Phi(x,u) + L\rho = 0 \Rightarrow \Phi(\omega(x,\rho),u)=0$$

This can always be solved, but only numerically.

Alternatively, one could start by specifying the form of the correction function and then determine the observer function Π to satisfy properties (P1) and (P2). The simplest choice is the linear function:

$$\omega(x,\rho) = x - M\rho \quad (15)$$

where M is a constant vector of adjustable parameters. Then, the choice

$$\Pi(x,u,\rho) = \Phi(x\text{-}M\rho,u) + M\rho \quad (16)$$

will make properties (P1) and (P2) be satisfied. Finally, the requirement in (P3) translates into

$$\frac{\partial\Phi}{\partial x} - \left(I - \frac{\partial\Phi}{\partial x}\right)M\frac{\partial h}{\partial x} \quad (17)$$

having desirable eigenvalues.

5. TWO-DEGREE-OF-FREEDOM NONLINEAR MULTIRATE CONTROLLERS

A nonlinear multirate controller using a closed-loop observer will now be developed using results from the two previous sections. Since the observer and state corrector of the previous section were for a SISO system, the first task is to generalize the results for multiple measurements. Consider the p + ℓ fast measurements in (1) given by:

$$\mathbf{y} = \begin{bmatrix} \mathbf{y}_f^I \\ \mathbf{y}_f^{II} \end{bmatrix}$$

A single-rate observer and state corrector with multiple measurements can be developed driven by **y**. The observer and corrector functions must satisfy the following properties (where $?(k) = \mathbf{y}(k) - h(\hat{\mathbf{x}}(k))$):

(P1) $\Pi(\mathbf{x},\mathbf{u},0) = \Phi(\mathbf{x},\mathbf{u})$

(P2) $x = \Pi(\mathbf{x},\mathbf{u},r) \Rightarrow \omega(\mathbf{x}, r) = \Phi(\omega(\mathbf{x}, r),\mathbf{u})$

(P3) the eigenvalues of $\dfrac{\partial\Phi}{\partial x} - \dfrac{\partial\Pi}{\partial\rho}\dfrac{\partial h}{\partial x}$ evaluated at reference conditions must assume desirable values.

Using the second alternative from the previous section, a simple choice is to start by specifying a correction function of the form:

$$\omega(\mathbf{x}, r) = \mathbf{x} - \mathbf{M}r \tag{18}$$

where **M** is a constant matrix of adjustable parameters. Then, the choice

$$\Pi(\mathbf{x},\mathbf{u}, r) = \Phi(\mathbf{x}\text{-}\mathbf{M}r, \mathbf{u}) + \mathbf{M}r \tag{19}$$

will make properties (P1) and (P2) be satisfied. Finally, the requirement in (P3) translates into

$$\frac{\partial\Phi}{\partial x} - \left(I - \frac{\partial\Phi}{\partial x}\right)\mathbf{M}\frac{\partial h}{\partial x} \tag{20}$$

having desirable eigenvalues.

The resulting corrected state estimates are then used in the model-algorithmic multirate controller in place of the model values. Following the same development, future changes of the output can be predicted by:

$$\begin{aligned}
&y_{ic}(k+1) - y_{ic}\left(\left[\frac{k}{N_i}\right]N_i\right) \\
&\qquad = h_i^1[\hat{\mathbf{x}}_c(k)] - h_i\left[\hat{\mathbf{x}}_c\left(\left[\frac{k}{N_i}\right]N_i\right)\right] \\
&y_{ic}(k+2) - y_{ic}\left(\left[\frac{k}{N_i}\right]N_i\right) \\
&\qquad = h_i^2[\hat{\mathbf{x}}_c(k)] - h_i\left[\hat{\mathbf{x}}_c\left(\left[\frac{k}{N_i}\right]N_i\right)\right] \\
&\qquad \vdots \\
&y_{ic}(k+r_i-1) - y_{ic}\left(\left[\frac{k}{N_i}\right]N_i\right) \\
&\qquad = h_i^{r_i-1}[\hat{\mathbf{x}}_c(k)] - h_i\left[\hat{\mathbf{x}}_c\left(\left[\frac{k}{N_i}\right]N_i\right)\right] \\
&y_{ic}(k+r_i) - y_{ic}\left(\left[\frac{k}{N_i}\right]N_i\right) \\
&\qquad = h_i^{r_i-1}[\Phi(\hat{\mathbf{x}}_c(k), \mathbf{u}(k))] - h_i\left[\hat{\mathbf{x}}_c\left(\left[\frac{k}{N_i}\right]N_i\right)\right]
\end{aligned} \tag{21}$$

where y_{ic} is the ith controlled output, i.e.

$$\mathbf{y}_{ic} \in \begin{bmatrix} \mathbf{y}_f^I \\ \mathbf{y}_s^I \end{bmatrix}$$

and is calculated on the basis of the corrected state estimates. The predicted changes of the output can be added to the latest available output measurement to obtain the following predictions of the output y_i:

$$\begin{aligned}
&\hat{y}_i(k+1) = y_i\left(\left[\frac{k}{N_i}\right]N_i\right) \\
&\qquad + h_i^1[\hat{\mathbf{x}}_c(k)] - h_i\left[\hat{\mathbf{x}}_c\left(\left[\frac{k}{N_i}\right]N_i\right)\right] \\
&\hat{y}_i(k+2) = y_i\left(\left[\frac{k}{N_i}\right]N_i\right) \\
&\qquad + h_i^2[\hat{\mathbf{x}}_c(k)] - h_i\left[\hat{\mathbf{x}}_c\left(\left[\frac{k}{N_i}\right]N_i\right)\right] \\
&\qquad \vdots \\
&\hat{y}_i(k+r_i-1) = y_i\left(\left[\frac{k}{N_i}\right]N_i\right) \\
&\qquad + h_i^{r_i-1}[\hat{\mathbf{x}}_c(k)] - h_i\left[\hat{\mathbf{x}}_c\left(\left[\frac{k}{N_i}\right]N_i\right)\right] \\
&\hat{y}_i(k+r_i) = y_i\left(\left[\frac{k}{N_i}\right]N_i\right) \\
&\qquad + h_i^{r_i-1}[\Phi(\hat{\mathbf{x}}_c(k), \mathbf{u}(k))] - h_i\left[\hat{\mathbf{x}}_c\left(\left[\frac{k}{N_i}\right]N_i\right)\right]
\end{aligned} \tag{22}$$

The output measurement y_i is taken only at the time instants $[k/N_i]N_i$, but the manipulated inputs are actuated at every k. For each of the outputs, a reference trajectory can be defined according to (4).

Matching the predictions with the reference trajectories gives a set of nonlinear algebraic equations that must be solved numerically online for the input vector:

$$
\begin{aligned}
&h_1^{r_1-1}\left[\Phi\left(\hat{\mathbf{x}}_c(k),\mathbf{u}(k)\right)\right]=\alpha_1 h_1^{r_1-1}\left[\hat{\mathbf{x}}_c(k)\right]\\
&\quad+(1-\alpha_1)\left[y_{1sp}-y_1\left(\left[\frac{k}{N_1}\right]N_1\right)+h_1\left[\hat{\mathbf{x}}_c\left(\left[\frac{k}{N_1}\right]N_1\right)\right]\right]\\
&\qquad\vdots \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad (23)\\
&h_m^{r_m-1}\left[\Phi\left(\hat{\mathbf{x}}_c(k),\mathbf{u}(k)\right)\right]=\alpha_m h_m^{r_m-1}\left[\hat{\mathbf{x}}_c(k)\right]+(1-\alpha_m)\\
&\bullet\left[y_{msp}-y_m\left(\left[\frac{k}{N_m}\right]N_m\right)+h_m\left[\hat{\mathbf{x}}_c\left(\left[\frac{k}{N_m}\right]N_m\right)\right]\right]
\end{aligned}
$$

The corresponding implicit algebraic function defined at the solution to the previous set of equations is given by

$$\mathbf{u}(k)=\Psi\left[\hat{\mathbf{x}}_c(k),\mathbf{w}(k)\right] \qquad (24)$$

where $\Psi[*,*]$ is the same function as that in the single-rate MAC controller and

$$w_i(k)=y_{isp}-y_i\left(\left[\frac{k}{N_i}\right]N_i\right)+h_i\left[\hat{\mathbf{x}}_c\left(\left[\frac{k}{N_i}\right]N_i\right)\right] \qquad (25)$$

The structure of the complete closed-loop system is shown in Figure 3.

6. A SIMULATION EXAMPLE

The nonlinear control methodology will now be applied to a chemical process. The system consists of a CSTR, where the exothermic reaction A +B→C takes place. The reactants flow into the CSTR in separate streams. The jacket inlet temperature and the flow rate of B can be manipulated to control the outlet temperature and the outlet concentration of B. The reactor outlet temperature is measured at every time instant, but the measurement of the outlet concentration of B is measured only every N time steps. A model for this process is as follows:

$$
\begin{aligned}
T(k+1)&=T(k)+\left[\frac{UA}{\rho C_p V}\left(T_j(k)-T(k)\right)\right]\Delta t\\
&\quad+\left[\frac{F_A\left(T_{A0}-T(k)\right)+F_B(k)\left(T_{B0}-T(k)\right)}{V}\right]\Delta t\\
&\quad+\left[\frac{(-\Delta H)}{\rho C_p}k_0 C_A(k)C_B(k)e^{-E/RT(k)}\right]\Delta t\\
T_j(k+1)&=T_j(k)+\left[\frac{UA}{m_j C_{pj}}\left(T(k)-T_j(k)\right)\right]\Delta t\\
&\quad+\left[\frac{F_j\rho_j}{m_j}\left(T_{ji}(k)-T_j(k)\right)\right]\Delta t \qquad (26)\\
C_A(k+1)&=C_A(k)-\left[k_0 C_A(k)C_B(k)e^{-E/RT(k)}\right]\Delta t\\
&\quad+\left[\frac{F_A C_{A0}-(F_A+F_B(k))C_A(k)}{V}\right]\Delta t\\
C_B(k+1)&=C_B(k)-\left[k_0 C_A(k)C_B(k)e^{-E/RT(k)}\right]\Delta t\\
&\quad+\left[\frac{F_B(k)C_{B0}-(F_A+F_B(k))C_B(k)}{V}\right]\Delta t
\end{aligned}
$$

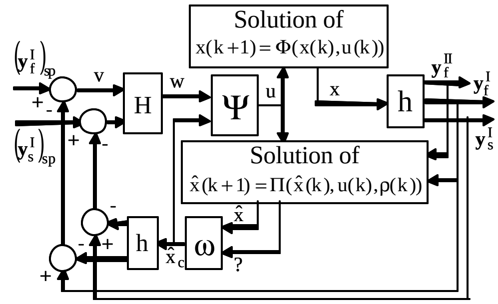

Figure 3: Structure of Nonlinear Multirate MAC with closed-loop observer

where the symbols used are common in chemical reactor engineering. The initial steady-state values of the outputs are T = 350 K and C_B = 0.781 kmol/m^3. The corresponding steady-state values of the inputs are T_{ji} = 358.4 K and F_B = 0.00013 m^3/s. The value used for each of the parameters is given in Table 1.

The observer and corrector were derived from the model equations (26) using (18) and (19). The observer was tuned using (20) and standard pole placement routines to calculate values for the M vector. The characteristic matrix of (26) is singular. The system was extended by adding a state equation, $F_B(k+1)=\zeta(k)$, and using $\zeta(k)$ as the manipulated input. The relative orders in the extended system are equal to 2 for both outputs, the characteristic matrix is nonsingular, and the inputs can be calculated from (23).

The response of the closed-loop system to simultaneous errors in three initial conditions of the observer states are shown in Figures 4 through 6. These figures show the tracking of the observer and the rejection of the initial condition errors.

Table 1: Parameter values for the example process

V = 1 m^3	-ΔH = 60000 kJ/kmol
F_A = 0.000325 m^3/s	R = 8.345 kJ/(kmol K)
T_{A0} = 300 K	E = 82800 kJ/kmol
C_{A0} = 5 kmol/m^3	k_0 = 1.2 x 10^9 m^3 kmol^{-1} s^{-1}
UA = 1.4 kJ/(s K)	ρ = 850 kg/m^3
C_p = 3.5 kJ/(kg K)	C_{B0} = 9 kmol/m^3
T_{B0} = 320 K	m_j = 500 kg
Cpj = 4.2 kJ/(kg K)	ρ_j = 100 kg/m^3
? t = 10 seconds	N = 20

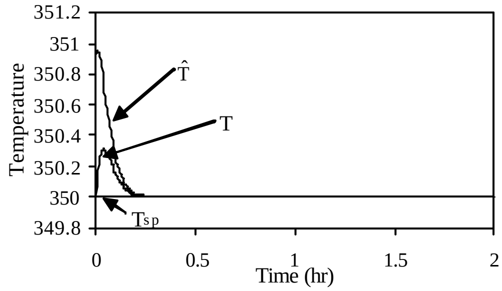

Figure 4: Response of T to a +1 K error in observer initial condition

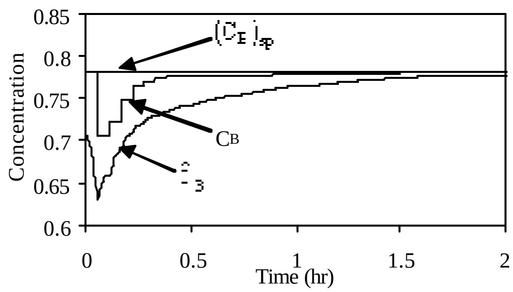

Figure 5 : Response of C_B to a -10% K error in initial condition

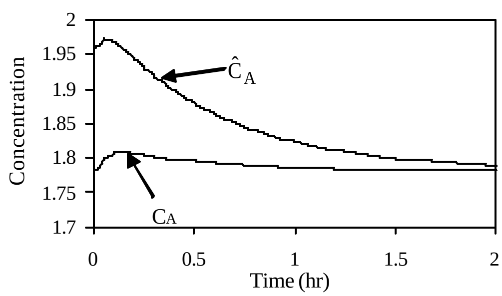

Figure 6: Response of C_A to a +10% K error in initial condition

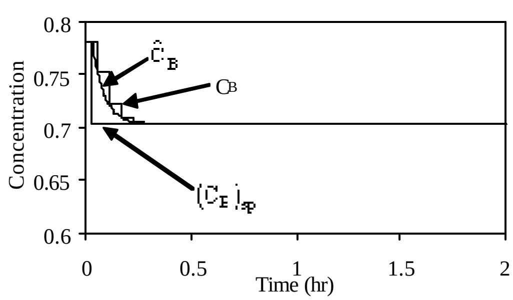

Figure 7 : Response of C_B to a -10% step in C_B set point concentration

The response of the closed-loop system to a -10% step decrease in the set point of C_B concentration is shown in Figure 7. The proposed controller results in a decoupled response, there fore there is no deviation from set point in T. This figure has been omitted for brevity.

The slower rate of sampling of C_B is evident from Figure 7. Simulation results showing the ability of the proposed controller to reject unmeasured disturbances have also been omitted for brevity.

8. REFERENCES

Bequette, B. W. (1991). “Nonlinear Predictive Control Using Multirate Sampling,” *Can. J. Chem. Eng.*, **69**, 136.

Lee, J. H.; Gelormino, M.; Morari, M. (1992). “Model Predictive Control of Multi-Rate Sampled-Data Systems: A State-Space Approach,” *Int. J. Control*, **55**, 153.

Lin, W.; Byrnes, C. I. (1995). “Remarks on Linearization of Discrete-Time Autonomous Systems and Nonlinear Observer Design,” *Syst. Cont. Lett.*, **25**, 31.

Mehra, R. K.; Rouhani, R. (1980). “Theoretical Considerations on Model Algorithmic Control for Nonminimum Phase Systems,” *Proc. ACC* TA8-B.

Niemiec, M. P.; Kravaris, C. (2002). “Nonlinear Multirate Model Algorithmic Control. 1. Theory,” *Ind. Eng. Chem. Res.*, **41**, 4054.

Ohshima, M.; Hashimoto, I.; Ohno, H.; Takeda, M.; Yoneyama, T.; Gotoh, F. (1994). “Multirate Multivariable Model Predictive Control and its Application to a Polymerization Reactor,” *Int. J. Control*, **59**, 731.

Richalet, J.; Rault, A.; Testud, J. L.; Papon, J. (1978). “Model Predictive Heuristic Control: Application to Industrial Processes,” *Automatica*, **14**, 413.

Soroush, M.; Kravaris, C. (1996). “Discrete-Time Nonlinear Feedback Control of Multivariable Processes,” *AIChE J.*, **42**, 187.

Wright, R A.; Kravaris, C. (2000). “Two-Degree-of-Freedom Output Feedback Controllers for Nonlinear Processes,” *Proc. ACC*, FM06-4.

Wright, R. A.; Kravaris, C. (2001). “Two Degree of Freedom Output Feedback Controllers for Discrete-Time Nonlinear Processes,” *Proc. ACC*, TP11-2.