Design Procedure of Sliding Mode Observers via Bond Graph

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Abstract: This work deals with a Bond Graph approach used to design sliding mode observers. The method is an extension of the Bond Graph technique designed for classical Luenberger observers. Two kind of sliding mode observers are analysed and designed by using the Bond Graph approach: the equivalent control method based sliding mode observers and the so-called modified Utkin observers.

Keywords: Bond graphs, bioprocesses, observers.

1. INTRODUCTION

Bond Graph method was introduced by Paynter, and further developed by Rosenberg & Karnopp, 1974, and Thoma, 1975. Over the last four decades there have been a lot of publications regarding the theory and application of Bond Graphs in different engineering domains (Gawthrop & Smith, 1996, Dauphin-Tanguy, 2000, Thoma & Ould Bouamama, 2000). The advantages of Bond Graph modelling are the following: offers a unified approach for all types of systems; allows to display the exchange of power in a system by its graphical representation; due to causality assignment it gives the possibility of localization of the state variables and achieving the mathematical model in terms of state space equations in an easier way than using classical methods; provides information regarding the structural properties of the system, in terms of controllability and observability. The Bond Graph approach is a powerful tool for modelling, analysis and design of different kind of systems, such as electrical (Mukherjee *et al.*, 2007), mechanical, hydraulic (Dauphin-Tanguy, 2000), thermal (Thoma & Ould Bouamama, 2000), chemical (Thoma & Ould Bouamama, 2000, Heny *et al.*, 2000, Couenne *et al.*, 2006), etc. This method provides a uniform manner to describe the dynamical behaviour for all types of physical systems and illustrates the exchange power in a system, which is normally the product between the effort and flow variables in the true Bond Graph. Besides this representation there is another one, in which the product effort-flow does not have the physical dimension of power, called pseudo Bond Graph, which is more suitable for chemical and biochemical systems (Heny *et al.*, 2000, Couenne *et al.*, 2006).

One of the most significant problems related to application of advanced control strategies in some key fields such as chemical and biochemical industry, robotics and aerospace, etc., remains the proper modelling of the processes. More precisely, it is necessary to obtain useful models for control purposes, taking in account the specificity of these processes. Numeorus problems arise from the absence of cheap and reliable instrumentation (in biotechnology, for example), and from the uncertainty concerning the structure and/or the parameters of the process model.

In theory, many of the control strategies suppose that the state variables are available; this fact is not always true in practice, so the state vector must be estimated for use in the control laws. In the past, several types of observers have been designed for the reconstruction of state variables: Kalman filter (Kalman, 1976), adaptive observers (Gevers & Bastin, 1986), high gain observers (Gauthier *et al.*, 1992, Selişteanu *et al.*, 2009), sliding mode observers (SMO) (Utkin, 1992, Walcott & Zak, 1986, Edwards & Spurgeon, 1994, Barbu & Caraman, 2007) and so on - see (Thein & Misawa, 1995) for some comparisons. Depending upon the particular application, all these observers can be used with suitable results. Sliding mode observers differ from more traditional observers in that there is a non-linear discontinuous term injected into the observer depending on the output estimation error. These observers are known to be much more robust than Luenberger observers, as the discontinuous term enables the observer to reject disturbances (Tan & Edwards, 2000). The observers based on the variable structure systems theory and sliding mode concept can be classified in two categories (Xiong & Saif, 2000): the equivalent control based methods and sliding mode observers based on the method of Lyapunov. The analysis of these two types of SMO (Edwards & Spurgeon, 1994, Xiong & Saif, 2000) shows that there exist some differences in terms of robustness properties.

From practical point of view, the selection of the switched gain for the equivalent control based SMO is difficult (in order to obtain a sliding mode without excessive chattering) (Edwards & Spurgeon, 1994). Also, there exists bounded estimation error for bounded modelling errors (the estimation will not be accurate when uncertainties are presented) (Xiong & Saif, 2000). The Lyapunov based SMO (the so-called Walcott-Zak observer) provides exact estimation for certain class of nonlinear systems under existence of certain class of uncertainties. However, the difficulty in finding the design and gain matrices is the main drawback of this observer. Consider the effect of adding a negative output feedback term to each equation of the Utkin observer. This results in a new error system (Şendrescu *et al.*, 2007). The addition of a Luenberger type gain matrix, feeding back the output error, yields the potential to provide robustness against certain classes of uncertainty.

Bond Graph approaches for building observers were developed in some works, such as: the first Bond Graph architecture of classical Luenberger observers (Karnopp, 1979), Bond Graphs for reduced order Luenberger observers (Pichardo-Almarza *et al.*, 2003), for high-gain observers (Pichardo-Almarza *et al.*, 2005a), for nonlinear observers applied to electrical transformers (Gonzalez-A & Nuñez, 2009), and for proportional-integral observers (Pichardo-Almarza *et al.*, 2005b). In this last work, several observers are designed by using the Bond Graph method; moreover, the gain matrices are calculated from the Bond Graph of the observers. The method is applied to a continuous stirred tank chemical reactor.

The objective of this work is to design two kind of SMO by using the Bond Graph approach: the equivalent control method based SMO and the so-called modified Utkin SMO. Furthermore, the gain matrices of SMOs are obtained through a Bond Graph approach based on a pole placement technique.

2. FUNDAMENTS OF SLIDING MODE OBSERVERS

The sliding mode control algorithms are often used in process control (electrical systems, robotics, chemical processes) and in the last years in the control of bioprocesses (Selişteanu *et al.*, 2007, Barbu & Caraman, 2007, Tokat, 2009, Kravaris, 2010). In this frame, an interesting approach is related to the design of SMOs for bioprocesses (Barbu & Caraman, 2007, Rahman *et al.*, 2010). The SMOs are much more robust than Luenberger observers, as the discontinuous term enables the observer to reject disturbances (Tan & Edwards, 2000, Şendrescu *et al.*, 2007).

Observers based on sliding mode approach first were developed for linear systems (Jalili *et al.*, 1997). Consider the following linear time-invariant system:

$$\begin{aligned} \dot{x} &= Ax + Bu, \\ y &= Cx, \end{aligned} \tag{1}$$

where $A \in \Re^{n\times n}$, $B \in \Re^{n\times p}, C \in \Re^{p\times n}$.

The classical observer problem to be considered is that of reconstructing the state variables using only measured output information. Without loss of generality we assume that rank $C = p$. It is also assume that the pair $\{C, A\}$ is observable and matrices A, B, C are known. In this case, the observed vector y may be represented as:

$$\begin{aligned} &y = C_a x_a + C_b x_b, \\ &x = (x_a, x_b),\ C_a \in \Re^{p\times(n-p)},\ \ C_b \in \Re^{p\times p},\ \ \det(C_b) \neq 0 \end{aligned} \tag{2}$$

Using the following linear transformation of state variable:

$$T_1 = \begin{bmatrix} I_{n-p} & 0 \\ C_a & C_b \end{bmatrix}, \tag{3}$$

the system (1) can be written in the form:

$$\begin{aligned} \dot{x}_a &= A_{11}x_a + A_{12}y + B_1 u, \\ \dot{y} &= A_{21}x_a + A_{22}y + B_2 u \end{aligned} \tag{4}$$

The corresponding sliding mode observer proposed by Utkin is given by:

$$\begin{cases} \dot{\hat{x}}_a = A_{11}\hat{x}_a + A_{12}\hat{y} + B_1 u + LM\,\mathrm{sgn}(\hat{y} - y) \\ \dot{\hat{y}} = A_{22}\hat{y} + A_{21}\hat{x}_a + B_2 u - M\,\mathrm{sgn}(\hat{y} - y) \end{cases} \tag{5}$$

where $(\hat{x}_a, \hat{y})$ are the estimates for (x_a, y), $L \in \Re^{(n-p)\times p}$ is a constant nonsingular feedback gain matrix, sgn is the signum function, and M is a strictly positive gain. If one define $\varepsilon_y = \hat{y} - y$ and $\varepsilon_a = \hat{x}_a - x_a$ then the following error system is obtained

$$\begin{cases} \dot{\varepsilon}_a = A_{11}\varepsilon_a + A_{12}\varepsilon_y + LM\,\mathrm{sgn}(\varepsilon_y) \\ \dot{\varepsilon}_y = A_{21}\varepsilon_a + A_{22}\varepsilon_y - M\,\mathrm{sgn}(\varepsilon_y) \end{cases} \tag{6}$$

Defining the following change of coordinates:

$$T_2 = \begin{bmatrix} I_{n-p} & L \\ 0 & I_p \end{bmatrix} \tag{7}$$

then the error system with respect to these new coordinates can be written as:

$$\dot{\tilde{\varepsilon}}_a = \tilde{A}_{11}\tilde{\varepsilon}_a + \tilde{A}_{12}\varepsilon_y \tag{8}$$

$$\dot{\varepsilon}_y = A_{21}\tilde{\varepsilon}_a + \tilde{A}_{22}\varepsilon_y - M\,\mathrm{sgn}(\varepsilon_y) \tag{9}$$

where:

$$\begin{aligned} \tilde{A}_{11} &= A_{11} + LA_{21}, \\ \tilde{A}_{12} &= A_{12} + LA_{22} - \tilde{A}_{11}L, \\ \tilde{A}_{22} &= A_{22} - A_{21}L. \end{aligned} \tag{10}$$

It can be shown that for large enough $M > 0$, a sliding mode motion can be induced on the output error state in (9). It follows that, after some finite time $\varepsilon_y = 0$ and $\dot{\varepsilon}_y = 0$. Equation (8) then reduces to

$$\dot{\tilde{\varepsilon}}_a = \tilde{A}_{11}\tilde{\varepsilon}_a \tag{11}$$

which by choice of L represents a stable system and so $\tilde{\varepsilon}_a \to 0$ as $t \to \infty$. Consequently $\hat{x}_a \to x_a$ and the remaining states can be constructed in the original coordinate system as

$$\hat{x}_b = C_b^{-1}(y - C_a \hat{x}_a) \tag{12}$$

The major practical difficulty in the above presented approach is the selection of an appropriate gain M to induce a sliding motion in finite time (Edwards & Spurgeon, 1994). Consider now the effect of adding a negative output error feedback term to each equation of the Utkin observer (5) (Xiong & Saif, 2000). This results in a new observer described by:

$$\begin{cases} \dot{\hat{x}}_a = A_{11}\hat{x}_a + A_{12}\hat{y} + B_1 u - G_1(\hat{y} - y) + LM\,\mathrm{sgn}(\hat{y} - y) \\ \dot{\hat{y}} = A_{22}\hat{y} + A_{21}\hat{x}_a + B_2 u - G_2(\hat{y} - y) - M\,\mathrm{sgn}(\hat{y} - y) \end{cases} \tag{13}$$

and in a new error system governed by:

$$\begin{cases} \dot{\tilde{\varepsilon}}_a = \tilde{A}_{11}\tilde{\varepsilon}_a + \tilde{A}_{12}\varepsilon_y - G_1\varepsilon_y \\ \dot{\varepsilon}_y = A_{21}\tilde{\varepsilon}_a + \tilde{A}_{22}\varepsilon_y - G_2\varepsilon_y - M\,\mathrm{sgn}(\varepsilon_y) \end{cases} \tag{14}$$

By selecting $G_1 = \tilde{A}_{12}$ and $G_2 = \tilde{A}_{22} - A_{22}^s$ where A_{22}^s is any stable design matrix of appropriate dimension, then

$$\begin{cases} \dot{\tilde{\varepsilon}}_a = \tilde{A}_{11}\tilde{\varepsilon}_a \\ \dot{\varepsilon}_y = A_{21}\tilde{\varepsilon}_a + A_{22}^s\varepsilon_y - M\,\mathrm{sgn}(\varepsilon_y) \end{cases} \tag{15}$$

In this form the (nominal) error system is asymptotically stable for $M\,\mathrm{sgn}(\varepsilon_y)$ because the poles of the combined system are given by $\sigma(\tilde{A}_{11}) \cup \sigma(A_{22}^s)$ and so lie in the open left half complex plane. The two gain matrices G_1 and G_2 yields the potential to provide robustness against certain classes of uncertainty.

3. THE BOND GRAPH IMPLEMENTATION

In order to use the Bond Graph approach for the construction of sliding mode observers, first the structural observability of the model must to be verified (Pichardo-Almarza *et al.*, 2005b). The next property, proposed by (Sueur & Dauphin-Tanguy, 1991) can be used:

Property 1. A Bond Graph model is structurally observable, if the next two conditions are satisfied:

(i) There exists at least a causal path linking each I and C-element in integral causality and a sensor De or Df in the Bond Graph in preferred integral causality.

(ii) All the I and C-elements in integral causality in the Bond Graph in preferred integral causality accept a derivative causality when a preferred derivative causality is assigned on the bond graph model. If it is not satisfied directly, a dualisation of some De or Df has to be performed in order to transform the remaining integral causalities.

The Bond Graph technique for constructing the SMOs is in fact an extension of the method for building Luenberger observers (Pichardo-Almarza *et al.*, 2003, Pichardo-Almarza *et al.*, 2005b).

First, the Bond Graph model of the sliding mode observer (5) will be implemented. When the state variable from (5) is associated with a C element, a modulated flow source will be used. Otherwise, if the state variable is associated with an I-element, a modulated effort source is used. In fact, these modulated flow or effort sources are used to introduce the output injection of the observer. Because the observer (5) consists of two differential equations, in the terms of Bond Graph approach we have:

$$\begin{aligned} \dot{\hat{x}}_a &= A_{11}\hat{x}_a + A_{12}\hat{y} + B_1 u + LM\,\mathrm{sgn}(\hat{y} - y) \\ &= A_{11}\hat{x}_a + A_{12}\hat{y} + B_1 u + LM\,\mathrm{sgn}(\varepsilon_y) \end{aligned},$$

with

$$\hat{x}_a = [\hat{p}_I \quad \hat{q}_C]^T,\ \dot{\hat{x}}_a = [\hat{e}_I \quad \hat{f}_C]^T \tag{16}$$

$$\begin{aligned} \dot{\hat{y}} &= A_{22}\hat{y} + A_{21}\hat{x}_a + B_2 u - M\,\mathrm{sgn}(\hat{y} - y) \\ &= A_{22}\hat{y} + A_{21}\hat{x}_a + B_2 u - M\,\mathrm{sgn}(\varepsilon_y) \end{aligned},$$

with

$$\hat{y} = [\hat{p}_I \quad \hat{q}_C]^T,\ \dot{\hat{y}} = [\hat{e}_I \quad \hat{f}_C]^T \tag{17}$$

where p_I, q_C are the generalised momentum and displacements, and e_I, f_C are the effort and flow variables of the inertial and capacitive elements for both state variables of the observer ($\hat{x}_a$ and $\hat{y}$).

Then, the Bond Graph models of the observer (16), (17) are obtained by using the structures presented in Figs. 1-2 for modulated flow sources and in Figs. 3-4 for modulated effort sources.

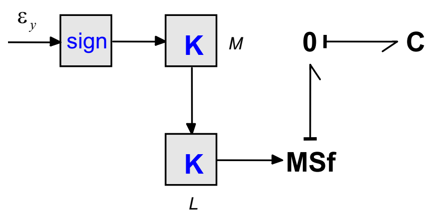

Fig. 1. Output injection in SMO – C element (first equation).

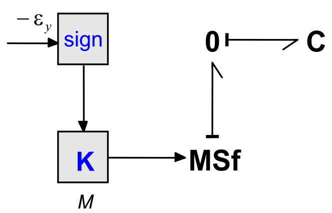

Fig. 2. Output injection in SMO – C element (second equation).

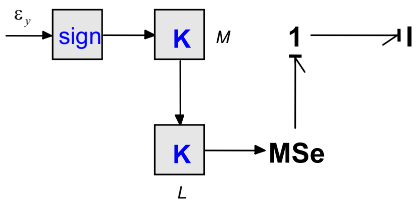

Fig. 3. Output injection in SMO – I element (first equation).

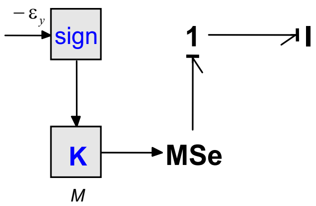

Fig. 4. Output injection in SMO – I element (second equation).

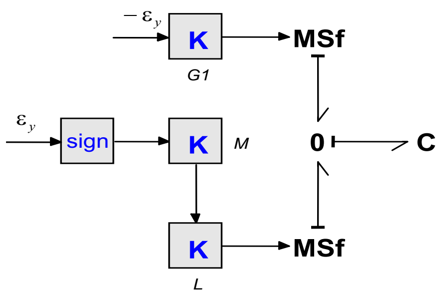

Fig. 5. Output injection in modified SMO – C element (first equation).

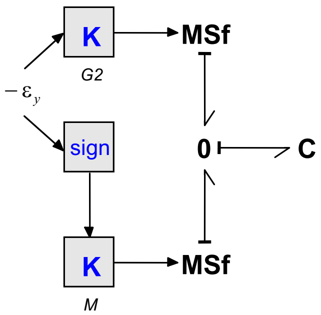

Fig. 6. Output injection in modified SMO – C element (second equation).

In a similar way, the Bond Graph model of the modified Utkin sliding mode observer (13) can be implemented. When the state variable from (13) is associated with a C element, a modulated flow source will be used; otherwise, for an I-element, a modulated effort source is used. In this case, a supplementary negative output error feedback is introduced in both equations of the modified Utkin SMO:

$$\dot{\hat{x}}_a = A_{11}\hat{x}_a + A_{12}\hat{y} + B_1 u - G_1\varepsilon_y + LM\,\mathrm{sgn}(\varepsilon_y)\,,$$

with

$$\hat{x}_a = [\hat{p}_I \quad \hat{q}_C]^T,\ \dot{\hat{x}}_a = [\hat{e}_I \quad \hat{f}_C]^T \tag{18}$$

$$\dot{\hat{y}} = A_{22}\hat{y} + A_{21}\hat{x}_a + B_2 u - G_2\varepsilon_y - M\,\mathrm{sgn}(\varepsilon_y)\,,$$

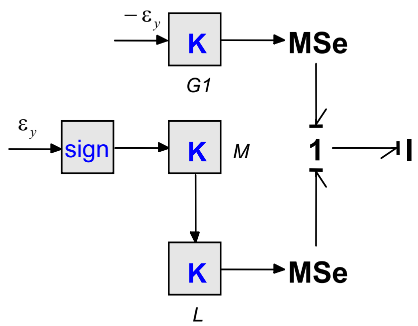

Fig. 7. Output injection in modified SMO – I element (first equation).

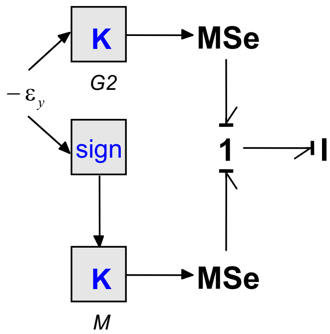

Fig. 8. Output injection in modified SMO – I element (second equation).

with

$$\hat{y} = [\hat{p}_I \quad \hat{q}_C]^T,\ \dot{\hat{y}} = [\hat{e}_I \quad \hat{f}_C]^T \tag{19}$$

Then, the Bond Graph models of the modified SMO (18), (19) are obtained by using the structures presented in Figs. 5-6 for modulated flow sources and in Figs. 7-8 for modulated effort sources.

4. COMPUTATION OF THE SMO GAINS

The full design of SMOs necessitates the calculus of some gains. In the case of the first SMO, the constant nonsingular feedback gain matrix L and the strictly positive gain M must to be chosen. Also, for the modified Utkin SMO it is necessary to find L, M and the injection matrices G_1 and G_2. The computation of these gains can be done by using the classical pole placement technique.

For the SMO described by the equations (5), it can be shown that for large enough $M > 0$, a sliding mode motion can be induced on the output error state. The appropriate choice of L leads to a stable error system. In fact, it is necessary to choose the matrix L such as the matrix $\widetilde{A}_{11}$ of the error system (11) to be Hurwitz. The choice of the coefficients of the characteristic polynomial of the matrix $\widetilde{A}_{11}$

$$\begin{aligned}\chi_{\widetilde{A}_{11}}(\lambda) &= \det(\lambda I_{n-p} - \widetilde{A}_{11}) = \det(\lambda I_{n-p} - (A_{11} + LA_{21})) \\ &= \lambda^{n-p} + \alpha_{n-p-1}\lambda^{n-p-1} + \cdots + \alpha_1\lambda + \alpha_0\end{aligned} \tag{20}$$

must be done such that eigenvalues $\lambda_i, i = \overline{0, n-p-1}$ to be in the open left half complex plane.

In a similar way, for the modified Utkin observer (13), the matrix L must be chosen such that the eigenvalues of (20) to be in the open left half complex plane. Moreover, in this case A_{22}^s is chosen as a predefined stable design matrix, with the characteristic polynomial:

$$\begin{aligned}\chi_{A_{22}^s}(\lambda) &= \det(\lambda I_p - A_{22}^s) = \\ &= \lambda^p + \beta_{p-1}\lambda^{p-1} + \cdots + \beta_1 \lambda + \beta_0\end{aligned} \tag{21}$$

with L and A_{22}^s fixed the calculation of G_1 and G_2 is straightforward:

$$\begin{aligned}G_1 = \widetilde{A}_{12} &= A_{12} + LA_{22} - \widetilde{A}_{11} L = \\ &= A_{12} + LA_{22} - (A_{11} + LA_{21})L\end{aligned} \tag{22}$$

$$G_2 = \widetilde{A}_{22} - A_{22}^s = A_{22} - A_{21}L - A_{22}^s \tag{23}$$

As a conclusion, the computation of all these gains can be possible by the calculation of the coefficients of some characteristic polynomials. This can be done in the Bond Graph models, considering the information signals associated with the components of gain matrices (the BG structures depicted in Figs. 1-8). In fact the coefficients $\alpha_i, i = \overline{0, n-p-1}$ and $\beta_j, j = \overline{0, p-1}$ are chosen such that the SMOs to have an appropriate stable behaviour.

Next, the pole placement method proposed by (Rahmani *et al.*, 1994) and used also by (Pichardo-Almarza *et al.*, 2005b) will be implemented in order to calculate the coefficients of the characteristic polynomial of a matrix directly from the Bond Graph model.

Definition 1. (Pichardo-Almarza *et al.*, 2005b). A causal cycle in a bond graph model is a closed path between several dynamical elements (I, C).

Definition 2. (Pichardo-Almarza *et al.*, 2005b). If a causal cycle contains k different dynamical elements (in integral causality), then the order of the causal cycle is equal to *k*.

A causal loop is defined as a closed path between two elements (I, C, R). Thus, according to Definitions 1 and 2, a causal loop (including at least a dynamical element) may be equal to a first-order causal cycle or a second-order causal cycle.

Definition 3. (Pichardo-Almarza *et al.*, 2005b). A k^{th}-order family of causal cycles is a set of different k^{th} -order causal cycles.

Theorem 1. (Pichardo-Almarza *et al.*, 2005b). The value of each coefficient ρ_i of the characteristic polynomial $\chi_A(\lambda)$ of a matrix A is equal to the total gain of the i^{th}-order families of causal cycles in the bond graph model:

$$\chi_A(\lambda) = \det(\lambda I_n - A) = \lambda^n + \rho_{n-1}\lambda^{n-1} + \cdots + \rho_1 \lambda + \rho_0 \tag{24}$$

The gain of each involved family of causal cycles must be multiplied by $(-1)^d$ if the family is constituted by d disjoint causal cycles.

The sliding mode observers design procedure requires the following steps:

(i) For the sliding mode observer of the type (5):

- Checking the structural observability of the Bond Graph model;

- Building the full Bond Graph model of the sliding mode observer by adding the Bond Graph structures from Figures 1-2 (for C-elements) or from Figures 3-4 (for I-elements);

- Choice of the strictly positive gain *M*;

- Computation of the observer gain matrix L by using the full Bond Graph model of the SMO previous obtained and by applying the Theorem 1.

(ii) For the modified sliding mode observer of the type (13):

- Checking the structural observability of the Bond Graph model;

- Building the full Bond Graph model of the modified SMO by adding the Bond Graph structures from Figs. 5-6 (for C-elements) or from Figs. 7-8 (for I-elements);

- Choice of the strictly positive gain *M* and of the stable matrix A_{22}^s;

- Computation of the observer gain matrix *L* by using the full Bond Graph model of the modified SMO (previous) obtained and by applying the Theorem 1;

- Calculation of the matrices G_1 and G_2 by using (22) and (23).

5. CONCLUSION

In this paper, a Bond Graph approach was proposed to design sliding mode observers. Two kind of sliding mode observers were designed: the equivalent control method based sliding mode observers and the so-called modified Utkin observers. The Bond Graphs of the SMOs were obtained and the observers' gains were computed by using a systematic procedure. In following researches, these observers will be applied to processes from chemical and biochemical industry. Another future challenge consists of the design of nonlinear SMOs via Bond Graph approach.

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