Chemical Engineering Science 136 (2015) 76–87

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Automated synthesis of control configurations for process networks based on structural coupling

Seongmin Heo [a], W. Alex Marvin [b], Prodromos Daoutidis [a,*]

[a] Department of Chemical Engineering and Materials Science, University of Minnesota, Minneapolis, MN 55455, USA
[b] BASF Corporation, 500 White Plains Road, Tarrytown, NY 10591, USA

HIGHLIGHTS

- Use the concept of relative degree to synthesize control configurations with favorable structural coupling.
- Propose an integer optimization formulation to synthesize fully decentralized control configurations.
- Propose a hierarchical clustering procedure to generate block decentralized configuration candidates.
- Illustrate the application of the method to a complex process network.

ARTICLE INFO

Article history:
Received 6 October 2014
Received in revised form
29 January 2015
Accepted 27 March 2015
Available online 4 April 2015

Keywords:
Control structure selection
Plantwide control
Process networks
Integer programming
Hierarchical clustering

ABSTRACT

In this paper, a method to systematically synthesize control configurations with favorable structural coupling is developed, using relative degree as a measure of such coupling. Initially, an integer optimization problem is formulated to identify optimal distributions of inputs and outputs (decentralized control configurations) that minimize the overall structural coupling in the network. Then, a hierarchical clustering procedure, which allows identifying groups of inputs and outputs that are strongly connected topologically (block decentralized control configurations), is proposed. The application of the method is illustrated through an example process network.

1. Introduction

Control structure design, i.e. the selection and pairing of manipulated inputs and controlled outputs, is a classic problem in control that has received a lot of attention in the literature (see e.g. van de Wal and de Jager, 2001). In process control in particular, this problem has been studied extensively in the context of plant-wide control design (see e.g. Rangaiah and Kariwala, 2012). Examples include (a) heuristics-based approaches whereby the selection and pairing are performed following logical rules (e.g. Price and Georgakis, 1993; Ng and Stephanopoulos, 1996; Luyben et al., 1997); (b) the concept of self-optimizing control for selecting controlled outputs as the basis for control structure design (e.g. Skogestad, 2000a,b; Baldea et al., 2008); (c) the concept of relative gain array (RGA) (e.g. Chang and Yu, 1990) and block RGA (e.g. Manousiouthakis et al., 1986; Kariwala et al., 2003); and (d) optimization based approaches using for example economic criteria (e.g. Heath et al., 2000; Psaltis et al., 2013, 2014; Ellis and Christofides, 2014).

The problem of control structure selection becomes particularly challenging for tightly integrated process networks, which are the rule rather than the exception in modern chemical and energy plants, and also in the context of smart manufacturing (Christofides et al., 2007). Integration results in significant economic benefits, but also limits the available degrees of freedom and leads to significant interactions that need to be addressed in controller design (including the selection of the control configuration). In a series of papers (Kumar and Daoutidis, 2002; Baldea et al., 2006; Jogwar et al., 2009), we have documented that whenever integration results in large rates of recovery and recycle of material and/or energy (compared to the input/output flows), a time-scale hierarchy develops: individual units evolve in a fast time scale (and are affected by the large internal and recycle flows) and slower network-level dynamics emerge (that are affected by the small external flows). This particular feature can be exploited for the selection of manipulated inputs acting in appropriate time scales to address individual process control objectives and network level objectives, in the context of hierarchical control.

However, integrated process networks are not necessarily characterized by a segregation of material and/or energy flows. The

* Corresponding author.
E-mail address: daout001@umn.edu (P. Daoutidis).

http://dx.doi.org/10.1016/j.ces.2015.03.049
0009-2509/

design of control systems for such networks is a challenging, open problem, that has been addressed, for example, using passivity-based control (e.g. Ydstie, 2002; Hudon and Bao, 2012; Tippett and Bao, 2013), distributed control (e.g. Rawlings and Stewart, 2008; Liu et al., 2009; Scattolini, 2009) and quasi-decentralized control (e.g. Mhaskar et al., 2007; Sun and El-Farra, 2008). Central to this problem is the pairing of manipulated inputs and controlled outputs, either in the form of single-input single-output controllers or multivariable ones. A promising approach to this end is to exploit the extensive work in network theory and graph theory towards identifying "communities" (of manipulated inputs and controlled outputs, in our case) whose members interact strongly among them, yet are weakly coupled to the rest of the network members (e.g. Girvan and Newman, 2002; Jiang et al., 2007). This community detection problem can be pursued using optimization of clustering parameters that capture the network connectivity (e.g. Newman, 2004, 2006) or through spectral graph theory (e.g. Varigonda et al., 2004). The former approaches are generally more easily scalable to larger networks.

For the pairing of manipulated inputs and controlled outputs, which we will refer to as the control configuration synthesis problem, a meaningful approach is to seek potential inputs and outputs that are strongly connected topologically. One measure of topological closeness is the concept of relative degree (Daoutidis and Kravaris, 1992). Relative degree essentially captures the directness of the effect of an input on an output, or the physical closeness between the two variables, and can be used to identify input/output clusters with favorable "structural coupling" in the above sense (Daoutidis and Kravaris, 1992; Schné and Hangos, 2011). Its generic calculation requires only structural information on the dynamic interactions in the network, and can be automated on the basis of an equation graph that captures these dynamic interactions.

In this paper, we develop a method to systematically synthesize control configurations with favorable structural coupling, using relative degree as a measure of such coupling. Initially, we formulate an integer optimization problem to identify optimal distributions of inputs and outputs (essentially decentralized control configurations) that minimize the overall structural coupling in the network. We then propose a hierarchical clustering procedure which allows identifying groups of inputs and outputs that are strongly connected topologically, and are thus block decentralized control configuration candidates. The proposed approach is flexible as it allows generating control configurations that span the entire gamut from fully decentralized ones to the fully centralized one. It can also be automated for ease of implementation. Its application is illustrated through a case study on an integrated energy system.

2. Relative degree as a measure of structural coupling

Let us consider a general state space model of the form:

$$\dot{x} = f(x) + \sum_{i=1}^{n_u} g_i(x) u_i$$
$$y_j = h_j(x), \quad j = 1, \ldots, n_y \tag{1}$$

where $x \in \mathbb{R}^{n_x}$ denotes the state variables, and $u_i, y_j \in \mathbb{R}$ denote the input variables and the output variables, respectively. f, g_i are vector fields on $\mathbb{R}^{n_x}$, and h_j are scalar fields on $\mathbb{R}^{n_x}$.

The relative degree between u_i and y_j, r_{ij}, is defined as the smallest integer that satisfies (Khalil, 2002)

$$\mathcal{L}_{g_i} \mathcal{L}_f^{r_{ij}-1} h_j(x) \not\equiv 0 \tag{2}$$

where $\mathcal{L}$ represents the Lie derivative, defined as

$$\mathcal{L}_f h(x) = \frac{\partial h(x)}{\partial x} f(x)$$

In Daoutidis and Kravaris (1992), it was shown that the relative degree can be interpreted as a measure of how *direct* the effect of an input is on an output, as it represents the number of integrations needed for an input to affect an output. It was also argued that the relative degree can be used as a measure of *physical closeness* between an input and an output as it captures the sluggishness of the input/output response (in effect representing an apparent dead time). Also, it was shown that the generic calculation of relative degree requires only structural information of a process, i.e. knowledge of the interdependencies among the process variables. This can be used to construct an *equation graph* where nodes represent the state, input and output variables, and edges represent the interdependencies among the process variables. Edges are added based on the following rules:

- there is an edge from node x_k to node x_l if $\partial f_l(x)/\partial x_k \not\equiv 0$,
- there is an edge from node u_i to node x_l if $g_{il}(x) \not\equiv 0$,
- there is an edge from node x_k to node y_j if $\partial h_j(x)/\partial x_k \not\equiv 0$,

where $f_l(x)$, $g_{il}(x)$ are the l-th element of $f(x)$, $g_i(x)$, respectively.

In such a graph, a *path* is defined as an open walk of nodes and edges of a graph such that no node is repeated. The *length* of a path is the number of edges contained in the path. An *input-to-output path* (IOP) is a path which starts from an input node and terminates at an output node. The relative degree r_{ij} is then related to the length of the shortest IOP connecting u_i and y_j of the equation graph as follows (Daoutidis and Kravaris, 1992):

$$r_{ij} = l_{ij} - 1 \tag{3}$$

Based on the above, relative degree can be used as a measure of structural coupling, i.e. coupling among the input/output variables based on their structural interdependencies, to provide guidelines for the design and evaluation of multi-loop control configurations. The procedure described in Daoutidis and Kravaris (1992) involves the following steps:

1. Compute the relative degrees between all the inputs and the outputs to form a relative degree matrix (RDM) whose elements are the relative degrees between the inputs and the outputs:
$$M_r = \begin{bmatrix} r_{11} & \cdots & r_{1n_y} \\ \vdots & \ddots & \vdots \\ r_{n_u 1} & \cdots & r_{n_u n_y} \end{bmatrix}$$
2. Rearrange the outputs such that the minimum relative degree in each column of the RDM falls on the major diagonal. Then, the diagonal elements of the rearranged RDM represent the relative degrees between the input/output pairs forming the control configuration with a favorable structural coupling. The off-diagonal relative degrees in a row capture the coupling between a specific input and the other outputs, while the off-diagonal relative degrees in a column capture the coupling between a specific output and the other inputs.
3. Evaluate the overall structural coupling for the particular input/output assignment by comparing the diagonal and the off-diagonal relative degrees. Specifically, the differences between off-diagonal and diagonal relative degrees in a row (i.e. $r_{ij} - r_{ii}$) and in a column (i.e. $r_{ji} - r_{ii}$) provide a measure of the overall structural coupling. The larger these differences are, the more favorable the control configuration is.

The above procedure is time consuming to apply to large scale process networks as each step needs to be executed manually. Also, only fully decentralized control configurations are considered. In what