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Selection of controlled variables: A novel perspective based on the singular energy of weighted graphs

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ABSTRACT

The optimal selection of controlled variables is a well-known plant-wide control subproblem. In this paper, a novel approach based on spectral graph theory is proposed. This strategy is useful from both graphical and mathematical point of views. It is shown here that if the closed-loop process is represented by a specific weighted graph, deviations in plant variables are bounded by the graph singular energy. Moreover, this graph-based methodology supports the fast interpretation of the magnitude and direction of influences between process variables at steady state. The suggested spectral approach is compared with the recently proposed minimum square deviation (MSD) methodology in detail. Indeed, both strategies have strong structural and behavioral resemblances, i.e. reducing specific deviations and improving the conditions of the subprocess to be controlled. The introduced graph representation is tested in the Shell oil fractionator process, giving a complete set of evaluations and results.

1. Introduction

Modern industrial processes are complex and highly interconnected; process plants operation is limited by environmental, economical and operational restrictions. As a consequence, they require the definition and implementation of proper control policies to attain the desired operation performance, maintaining stability and minimizing the effects of unmeasured disturbances.

The plant-wide control (PWC) area addresses the above stated problem from a global perspective. Some of the objectives of PWC are the optimal selection of controlled and manipulated variables (CVs and MVs), the input–output variable pairing, the controller structure (decentralized or centralized) and tuning. Most of these decisions are combinatorial problems in nature, which generally are solved by using heuristic concepts as well as engineering knowledge. While the processes dimension (i.e. amount of inputs and outputs) increases this heuristic treatment becomes quickly impractical, and the problem is frequently reduced ad-hoc generating suboptimal solutions. In this context, a systematic and generalized tool for PWC design is very helpful.

There are several approaches for dealing with the PWC problem, most of them based on process control and system analysis theories (Khaki-Sedigh & Moaveni, 2009; Skogestad & Postlethwaite, 2005). These methodologies range from simple steady-state analysis to complex frequency-based optimization routines. The systematics, generalization, and efficiency of such strategies are varied. The development of scalar indexes are welcomed by process and control engineers because they promote their use into optimization algorithms which systematize and generalize the PWC problems. An example of such methodologies is the recently appeared minimum square deviation (MSD) approach (Molina, Zumoffen, & Basualdo, 2011; Zumoffen & Basualdo, 2012, 2013). MSD uses the sum of square deviations (SSD) and the net load evaluation (NLE) indexes to quantify several steady-state deviations of the process variables at closed-loop. These indexes are integrated into combinatorial problems and multi-objective binary optimization algorithms to evaluate the multivariate process interaction caused by changes on set points and disturbances.

In this work a new perspective for representing and solving some PWC subproblems is presented. The motivation here, relies on the general idea of unifying the process information management (control, modeling, monitoring) via spectral graph theory. Due to the graphical potential and the well-defined mathematical background of this theory, the classical control/process engineers' tasks could be improved with suitable information (quantity and quality). In this context, the work proposed here, summarizes interesting preliminary results related to the first step the PWC, addressed from the spectral graph point of view. It is shown that some PWC subtasks such as the optimal CVs selection can be

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Nomenclature

Acronyms

CVs	controlled variables
DVs	disturbances variables
IMC	internal model control
MSD	minimum squared deviation
MTF	matrix of transfer functions
MVs	manipulated variables
NLE	net load evaluation
PWC	plant-wide control
SSD	sum of squared deviations
UVs	uncontrolled variables

Variables

$\mathbf{A}$	adjacency matrix
$\mathbf{A}_w$	weighted adjacency matrix
$\mathbf{A}_w^{cl}$	weighted adjacency matrix – closed-loop
$\mathbf{d}(s)$	disturbance vector
$\mathbb{E}(G)$	energy of graph G
$\mathbb{E}_s(G)$	singular energy of graph G
$\mathbf{e}(i)$	vector with unitary entry in the ith location
$\mathbf{D}(s)$	disturbance MTF
$\mathbf{D}_r(s)$	disturbance MTF for UVs
$\mathbf{D}_s(s)$	disturbance MTF for CVs
$\mathbf{F}(s)$	diagonal low pass MTF filter
$G(V, E)$	undirected weighted graph
$\mathbf{G}(s)$	process MTF
$\mathbf{G}_c(s)$	controller MTF
$\mathbf{G}_r(s)$	process MTF for UVs
$\mathbf{G}_r(s)$	process MTF for CVs
$\tilde{\mathbf{G}}_s(s)$	process model MTF for CVs
m	number of outputs
n	number of inputs
p	number of disturbances
s	Laplace variable
SSD($\mathbf{a}$)	sum of squared deviations of $\mathbf{a}$
t	time
$\mathbf{u}(s)$	input vector
$\mathbf{y}(s)$	output vector
$\mathbf{y}_r(s)$	UVs vector
$\mathbf{y}_s(s)$	CVs vector
$\mathbf{y}_s^{sp}(s)$	set point vector

Greek symbols

γ	condition number
λ_i	ith eigen value
σ_i	ith singular value
$\underline{\sigma}$	minimum singular value
$\overline{\sigma}$	maximum singular value

efficiently solved by analyzing the spectral properties of a properly defined weighted graph. Before going into further details, let us introduce some general graph concepts.

Many real-world situations can conveniently be represented by a diagram consisting of a set of vertices joined by a set of edges. For example, vertices could be people, communication centers or process variables, and the corresponding edges could represent friendship links, communications links and interactions degree, respectively. A mathematical abstraction of these situations led to the concept of graph (Bondy & Murty, 1985). A graph can be represented by its adjacency matrix $\mathbf{A}$; the analysis of $\mathbf{A}$ based on eigen values, eigen vectors, singular values and energy (Gutman & Shao, 2011; Nikiforov, 2007) is called the theory of graph spectra. This theory attempts to utilize linear algebra including, in particular, the well-developed theory of matrices, for purposes of graph theory and its applications (Cvetković, Rowlinson, & Simić, 2010).

Spectral graph theory has acquired great relevance in the last decade, particularly in the computer science area. An excellent survey of these applications can be found in Cvetković and Simić (2011). Other research areas such as process engineering have very few applications of this spectral approach. Anyway, there are some works related to graph theory such as Castaño Arranz and Birk (2012) where new methods for the analysis of complex processes are suggested. The authors formulated a flexible framework to help the designers in comprehending a process by representing structural and functional relationships. Yang, Shah, and Xiao (2012) suggested a fusion of information from process data and process connectivity. Signed directed graphs are used to capture the process topology and connectivity, thus depicting the causal relationships between process variables. Gutierrez-Perez, Herrera, Perez-Garcia, and Ramos-Martinez (2011) introduced a methodology based on spectral measurements of graphs to establish the relative importance of areas in water supply networks. These areas are analyzed using a flexible method of semi-supervised clustering.

Here, we present a methodology to optimally select CVs based on the singular energy of a graph. We found that if the closed-loop process is represented by a weighted graph, its energy (based on its adjacency matrix $\mathbf{A}$) is strongly related to deviations in some plant variables. Moreover, the singular energy is an upper bound for the interaction effects between all the vertices of the weighted graph in a SSD sense (Frobenius norm). Explicitly, it is show that the SSD concept applied to the overall graph structure is equivalent to quantify the deviations in the vertices corresponding to MVs and uncontrolled variables (UVs) only.

This result shows a clear structural resemblance with the approach called MSD-SSD presented by Zumoffen and Basualdo (2012, 2013), but in this case from a spectral graph point of view. Hence, the optimal CVs selection can be performed by minimizing the singular energy of the graph. Furthermore, the analysis shows that this minimization has similar properties to those obtained using the SSD approach. Particularly, both methodologies tend to improve the matrix-properties of the subprocess to be controlled (i.e. tend to maximize their minimum singular value). This is an important quality, strongly related to the final closed-loop behavior, as stated by (Garcia & Morari, 1985; Grosdidier, Morari, & Holt, 1985; Skogetad & Morari, 1987).

The work is organized as follows. Section 2 gives a background on some already existing tools and methodologies. Section 2.1 presents a simplified description of the MSD approach suggested by Zumoffen and Basualdo (2012, 2013). In particular, the optimal CVs subproblem is described. In Section 2.2 the main graphs concepts used in this work are defined. The most important contribution of this paper is introduced in Section 3, where the main links between the classical SSD and the singular energy-based approaches are highlighted. Both methodologies are applied to the well-known Shell oil fractionator process in Section 4, where several simulation results are presented. Conclusions and future work are discussed in Section 5.

2. Background and tools

2.1. Minimum square deviation

The minimum square deviation (MSD) approach suggested by Zumoffen and Basualdo (2012, 2013) addresses several PWC tasks such as: the optimal selection of CVs and MVs, the input–output pairing, the controller interaction degree (decentralized, full or sparse), and the controller oversizing analysis (order). In this case, for clarity, only a simplified version of the MSD methodology is considered.