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Optimal process and control design under uncertainty: A methodology with robust feasibility and stability analyses

M. Trainor, V. Giannakeas, C. Kiss, L.A. Ricardez-Sandoval *

Department of Chemical Engineering, University of Waterloo, Waterloo, Ont., Canada N2L 3G1

HIGHLIGHTS

- An iterative algorithm for simultaneous design and control is presented.
- Disturbances are treated as random time-dependent bounded perturbations.
- Robust feasibility and stability analyses are introduced in this method.
- The algorithm is tested with a ternary distillation system.
- The method is a practical tool for optimal design of systems under uncertainty.

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ABSTRACT

This paper presents a new methodology for the optimal process and control design of dynamic systems under uncertainty. Robust feasibility and stability analyses are incorporated within the proposed methodology to ensure process dynamic operability and asymptotic stability. These analyses are formulated as convex mathematical problems; thus, the present approach is computationally attractive since it does not require the solution of an MINLP to evaluate dynamic feasibility and stability as it has been proposed by recent dynamic optimization-based methodologies. A norm-bounded metric based on Structured Singular Value (SSV) analysis is employed to estimate the worst-case deviation in the process constraints in the presence of critical realizations in the disturbances. The robust stability test is based on Lyapunov theory and guarantees process asymptotic stability. Accordingly, the optimal process and control design alternative obtained by the method proposed here is dynamically feasible and asymptotically stable since it accommodates the most critical realizations in the disturbances. A ternary distillation system featuring a rigorous tray-by tray process model is used to illustrate the application of the proposed method.

1. Introduction

Integration of process design and control, also known as simultaneous design and control, has emerged as an attractive alternative to overcome the limitations imposed by the traditional sequential design approaches. The key in integration of design and control is to obtain an optimal design by conducting a steady state analysis, which ensures that the design meets its goals at steady-state at minimum capital and operating cost, combined with a controllability analysis, which seeks for a suitable control structure that can meet the process operational and performance specifications in closed-loop. This activity is not a simple task to perform since the steady-state analysis and the evaluation of the system's dynamic performance may have conflicting objectives (Luyben, 2004). Despite the efforts that have been made in this field, a unified framework for simultaneous of design and control with embedded robust stability criteria is not currently available. Number of approaches that address the integration of design and control have been attempted in the literature, e.g., controllability index-based methods (Lenhoff and Morari, 1982; Palazoglu and Arkun, 1986, 1987), dynamic optimization-based methods (Bahri et al., 1997; Bansal et al., 2002; Kookos and Perkins, 2001; Malcolm et al., 2007; Mohideen et al., 1996a; Swartz, 2004), robust metrics-based methods (Hamid et al., 2010; Francisco et al., 2011; Munoz et al., 2012; Gerhard et al., 2005, 2008; Lu et al., 2010; Ricardez-Sandoval et al., 2009a; Ricardez Sandoval et al., 2008) and recently, probabilistic-based methods (Ricardez-Sandoval, 2012). Review articles on integration of design and control are available elsewhere (Ricardez-Sandoval et al., 2009b; Seferlis and Georgiadis, 2004; Sakizlis et al., 2004; Yuan et al., 2012).

* Corresponding author. Tel.: +1 519 888 4567x38667; fax: +1 519 746 4979.
E-mail address: laricard@uwaterloo.ca (L.A. Ricardez-Sandoval).

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The evaluation of multiple process design and control structure alternatives is essential to determine an optimal design. While structural changes in the process design and the control structure can be incorporated by adding integer decisions in the analysis, the addition of integer variables increases the problem's dimensionality thus making it computationally intensive or even prohibitive for large-scale industrial applications. To date, a few simultaneous design and control methods have included structural decisions in their formulations. A subset of those methods were developed using controllability metrics (Alhammadi and Romagnoli, 2004; Luyben and Floudas, 1994; Seferlis and Grievink, 2001). While simple to implement, those methods specified an optimal design that may only be valid at steady-state or around nominal operating point. Thus, those designs may become infeasible or unstable when the effect of disturbances moves the system away from its nominal operating point. Formal dynamic optimization formulations that include structural decisions are also available (Bahri et al., 1997; Bansal et al., 2002; Kookos and Perkins, 2001; Mohideen et al., 1996a, 1996b; Sakizlis et al., 2004). Those methods propose an iterative decomposition framework, composed of a dynamic flexibility analysis and a dynamic feasibility analysis, to attain the optimal process design under the effect of disturbances and model parameter uncertainty. An overview of the iterative algorithm proposed by those methods is presented elsewhere, e.g., see Fig. 1 in Sakizlis et al. (2004). In those methods, the dynamic flexibility and feasibility analyses are formulated as complex optimization problems. Also, the optimal design specified by those approaches is obtained under the assumption that the disturbance dynamics follow a user-defined time-dependent function with unknown (critical) parameters. Hence, process constraints may be exceeded when the process is subject to time-trajectories in the disturbances that do not follow the disturbance dynamic model used by the user to assess the optimal design.

The evaluation of the process asymptotic stability in the presence of disturbances is another fundamental aspect in simultaneous design and control. It has been shown that optimal design and control schemes specified by methodologies that did not account for a formal stability test have been found to be unstable (Mohideen et al., 1997). To the authors' knowledge, very few methodologies that consider structural changes in the design have included a stability analysis in their formulations, e.g., Malcolm et al. (2007), Mohideen et al. (1996a, 1997) and Sakizlis et al. (2004). In general, the stability analysis is introduced as a set of constraints in the dynamic feasibility analysis, usually posed as an MINLP. Thus, the addition of the stability criterion within the feasibility test makes the evaluation of the MINLP formulation even more challenging, especially for large-scale complex systems.

The aim of this paper is to present a new simultaneous design and control methodology that accounts for structural decisions in the analysis. The proposed methodology includes a dynamic flexibility analysis, a robust dynamic feasibility analysis, and nominal and robust stability analyses. Two new formulations are developed here to evaluate dynamic feasibility and stability. The new formulations, based on methods borrowed from robust control theory, are formulated as convex mathematical problems for which efficient optimization algorithms exists. This represents an attractive feature in the present approach since previous methodologies have evaluated the system's dynamic feasibility and stability by solving an intensive MINLP formulation. The robust dynamic feasibility and stability formulations presented in this work assume that disturbances are random time-dependent perturbations bounded by upper and lower limits. This disturbance description is more general than that used by previous methods, i.e., the present method does not require the specification of a disturbance time-dependent function with critical parameters. Thus, the robust feasibility and stability formulations included in the present methodology enable the specification of an optimal design that can maintain the dynamic operability of the system feasible and stable in the presence of critical realizations in the disturbances.

A few methodologies for the integration of design and control of large-scale systems have been proposed by one of the authors (Ricardez-Sandoval et al., 2009c, 2010, 2011). Those methodologies assumed that the process flowsheet and the control structure remained fixed during the calculations, i.e., those methods only accounted for the sizing of the process units and the specification of the controller tuning parameters for the pre-established process flowsheet and control structure, respectively. The present approach represents an improvement to the previous methods since, in addition to the specification of the optimal size of the units and controller tuning parameters, structural decisions in both the process flowsheet and the control structure are explicitly accounted for in the analysis. This feature enables the specification of highly integrated and economically attractive systems that those obtained with the previous methods proposed by the corresponding author. In addition, the iterative decomposition framework proposed in this study is new and includes formulations that have not been previously considered for simultaneous design and control methods that account for structural decisions in the analysis.

This paper is structured as follows: Section 2 presents the simultaneous design and control methodology proposed in this work. Section 3 introduces a ternary distillation system, which is used as a case study to illustrate the benefits of the present methodology. The design obtained by the present approach is presented in this section and compared to those obtained by a sequential process design strategy and a set of dynamic flexibility analysis. Conclusions are stated at the end of this article.

2. Simultaneous design and control design methodology

A schematic of the iterative decomposition algorithm proposed in this work is presented in Fig. 1. As shown in this figure, the algorithm includes a dynamic flexibility analysis, a robust feasibility analysis and two stability analyses. Definitions, assumptions and the algorithm initialization are described next followed by the presentation of each of the analyses included in the present methodology.

Definitions, assumptions and initialization

The variables used to describe the present methodology are as follows:

$\mathbf{x}(t) \in \Re^{n_x}$: n_x time differential state variables of the system.
$\mathbf{y}(t) \in \Re^{n_y}$: n_y output (controlled) time-varying variables of the system.
$\boldsymbol{\rho}(t) \in \Re^{n_\rho}$: n_ρ manipulated (time-varying) variables available for control.
$\mathbf{d}(t) \in \Re^{n_d}$: n_d time-varying disturbances affecting the system.
$\mathbf{c}(t) \in \Re^{n_c}$: n_c time differential state variables of the control algorithms included in the control scheme.
$\boldsymbol{\eta} \in \Re^{1\times n_\eta}$: n_η process design variables that cannot be adjusted during the operation of the system.
$\mathbf{v} \in \Re^{1\times n_v}$: n_v process set points at steady-state. This vector includes the controlled variables' set points ($\mathbf{y*} \in \Re^{1\times n_y}$) and the nominal (steady-state) values in the manipulated variables ($\boldsymbol{\rho}_{nom} \in \Re^{1\times n_\rho}$).
$\boldsymbol{\zeta} \in \Re^{1\times n_\zeta}$: n_ζ controllers' tuning parameters, e.g., the gain and the time constant in a PI controller.
$\boldsymbol{\omega} \in \{0,1\}^{1\times n_\omega}$: vector of n_ω binary variables associated with the process flowsheet topology.
$\boldsymbol{\kappa} \in \{0,1\}^{1\times n_\kappa}$: vector of n_κ binary variables associated with the topology of the control system.