Chemical Engineering Science 172 (2017) 434–443

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Community-based synthesis of distributed control architectures for integrated process networks

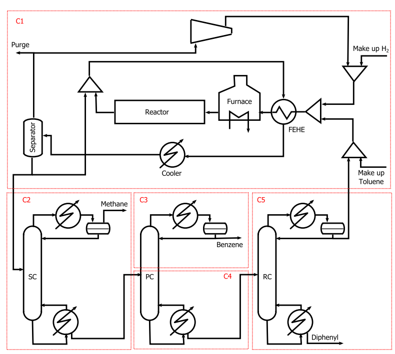
Sujit Suresh Jogwar [a,*], Prodromos Daoutidis [b]

[a] Department of Chemical Engineering, Indian Institute of Technology, Bombay, Powai, Mumbai 400076, India
[b] Department of Chemical Engineering & Materials Science, University of Minnesota, 421 Washington Ave SE, Minneapolis, MN 55455, United States

HIGHLIGHTS

- Community structure is used to design distributed control architecture.
- New interactivity measure is used to classify inputs, states and outputs.
- Graph theory-based synthesis method is fast, efficient, flexible and scalable.
- Application to several industrially relevant example systems is discussed.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 29 December 2016
Received in revised form 1 May 2017
Accepted 22 June 2017
Available online 23 June 2017

Keywords:
Graph theory
Multivariable control
Integrated networks
Distributed control
Community structure

ABSTRACT

In this paper, we propose a graph-theoretic framework for designing architectures for distributed control. Specifically, the popular concept of community structure is used to decompose an integrated network into multiple sub-networks with minimum interactions. The state space of the network is represented as an equation graph (directed). Communities identified on this graph represent sub-controllers for the distributed control system. A quality measure ‘interactivity’ is defined to compare such decompositions. The proposed method has many advantages (e.g. possibility of non-square controllers, provision to ensure controllability and observability, scalability, etc.) over existing approaches. The effectiveness of the proposed framework is illustrated via several industrially relevant examples.

1. Introduction

Advances in computer-aided design frameworks have resulted in highly integrated networks. Design engineers, set with the objectives of low capital cost, energy cost, floor space, etc., have resorted to synergistic interconnections of subsystems to achieve optimal designs. While such integrated networks document significant economic advantages at the design stage, they pose unique control challenges during the operational phase.

Integrated networks are characterized by strong interactions among state variables and reduced degrees of freedom (Kumar and Daoutidis, 2002). As an integrated network involves coupling between various sections of the system, control of individual sections, as in the case of decentralized control, is generally not effective (Cui and Jacobsen, 2002). These individual regulatory loops are frequently activated owing to disturbance propagation through coupling channels. On the other hand, a fully centralized controller can, in principle, account for all these interactions and provide

* Corresponding author.
E-mail addresses: jogwar@iitb.ac.in (S.S. Jogwar), daout001@umn.edu (P. Daoutidis).

http://dx.doi.org/10.1016/j.ces.2017.06.043
0009-2509/© 2017 Elsevier Ltd. All rights reserved.

satisfactory performance. However, design and tuning of such a controller is not a trivial task and often leads to unsatisfactory performance in real systems (Kumar and Daoutidis, 2002). Distributed control finds itself at an optimal position between these two extreme architectures (see Fig. 1). In distributed control, communications between controllers can be effectively used for stabilization and/or performance improvement.

Distributed control has been widely used to control networked systems. For example, Camponogara et al. (2002) has shown the potential of distributed control for load frequency control in power electronics. Vehicular formations can be effectively controlled using cooperative distributed control (Olfati-Saber and Murray, 2002). Distributed model predictive control has found many applications in process systems, especially in the context of (material and energy) integrated systems (Liu et al., 2009; Scattolini, 2009; Stewart et al., 2010; Tippett and Bao, 2013a). Similarly, distributed control has also been effectively exploited in robotics (Bullo et al., 2009), artificial intelligence (Weiss, 1999), and biological systems (Passino, 2002).

Most of the work in the area of distributed control has focused on feasibility, stability and optimality of the control solution for a given distributed architecture. Synthesis of the distributed architecture has received limited attention and it is quite common to decompose the system and control problem along a physical layout (Wu, 2003). A decomposition of the network based on connectivity information for distributed estimation has been proposed in Yin et al. (2016). In a different vein, decomposition or partition of the state-space for complex dynamical systems, motivated by reduced computational effort for the design and analysis of controllers and observers for high-dimensional systems, has been pursued for the design of decentralized controllers (Siljak, 2011). Graph-based algorithms such as hierarchical lower block triangular (LBT) decomposition (Sezer and Siljak, 1981) and nested ε-decomposition (Sezer and Šiljak, 1986) have been developed to decompose a complex system into interconnected subsystems by extracting information from the underlying state equations.

Recent work on control architecture synthesis using concepts from network theory has opened a new direction for systematic decomposition of process networks. Using input-output connectivity (quantified by relative degree), a framework for generating a hierarchy of control architectures ranging from centralized to decentralized ones via agglomerative or divisive clustering has been proposed (Heo et al., 2015; Heo and Daoutidis, 2016); a graph–theoretic formulation of this method along with the a posteriori selection of the optimal architecture in terms of the strength of the inter/intra-cluster interactions was proposed in Kang et al. (2016). A combined connectivity/response sensitivity interaction measure embedded in an input/output bipartite graph and used for decomposition of input/output sets was proposed in Tang and Daoutidis (2017). However, these approaches identify just input/output communities and do not give insights on information to be communicated between the corresponding control blocks as they do not incorporate state variables.

This paper aims to introduce a framework for distributed architecture synthesis through the decomposition of the *overall* state-space model of a network into an optimal number of sub-networks with minimal interactions among them. We use structural connectivity between inputs, states and outputs to quantify interactions, and adopt the well-known concept of community architecture to systematically decompose the network into sub-networks with strong intra-network and weak inter-network interactions. In this setting, the corresponding distributed control architecture follows naturally, wherein inputs and outputs in each sub-network are paired using one (SISO or MIMO) sub-controller and the connections between sub-networks (input-state or state-state edges) represent information sharing. A new quality measure, *interactivity*, closely related to the notion of modularity of networks is defined to judge the quality of the decomposition.

The rest of the paper is organized as follows. Section 2 reviews fundamental concepts in the community-based framework for analysis of complex networks. Section 3 presents the community-based approach for the synthesis of distributed control architectures. Section 4 illustrates the application of the proposed methodology to industrially relevant example systems. Section 5 discusses the advantages, limitations and possible extensions of the proposed framework.

2. Community structure in complex networks

The presence of a community structure *i.e.* groups with denser intra-group connections compared to inter-group connections, is a very common feature of large-scale networks (Fortunato, 2010). Fig. 2 shows a community structure for an arbitrary network. Identification of the community structure in large-scale networks helps understand and visualize the network, and has thus received tremendous attention in the last decade. A community-based analysis framework has been used to elucidate interactions and clustering phenomena in social (Wakita and Tsurumi, 2007; Blondel et al., 2008; Leskovec et al., 2008; Porter et al., 2009), ecological (Raymond and Hosie, 2009; Fortuna et al., 2010; Thomas et al., 2014), biological and process networks (Holme et al., 2003; Chen and Yuan, 2006; Jiang et al., 2007; Lewis et al., 2010; Junker and Schreiber, 2011). It is found that members of a community tend to exhibit similar properties or roles. For example, communities in a network of World Wide Web typically correspond to information on a related topic. In metabolic networks, they represent functional modules.

Graph theory has been efficiently used to develop algorithms to divide a network into meaningful communities. A large number of methods, such as graph partitioning, hierarchical clustering, spectral clustering, modularity optimization, block modeling, clique percolation, etc. have been developed for community detection (Fortunato, 2010). These methods broadly follow an agglomerative or divisive approach. In the agglomerative approach, one starts with a graph with only nodes (empty graph) and edges are added between nodes with the highest *similarity*. On the other hand, divisive algorithms begin with the entire network and edges between least *similar* nodes are successively deleted. Both these approaches result in a hierarchy of solutions with varying number of commu-

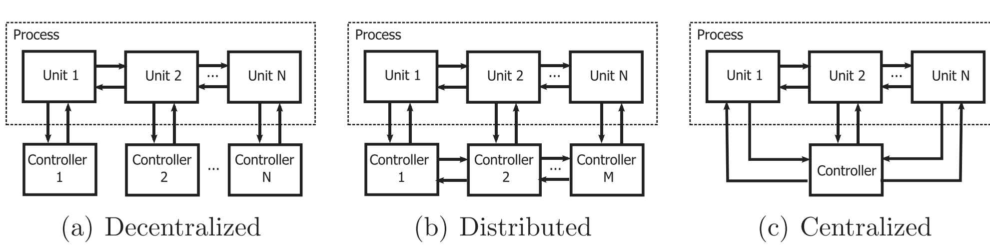


Fig. 1. Control architectures.