Chemical Engineering Science 136 (2015) 2–19

Contents lists available at ScienceDirect

Chemical Engineering Science

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

# Reconfigurable distributed model predictive control

Michael James Tippett, Jie Bao*

*School of Chemical Engineering, The University of New South Wales, UNSW, Sydney, NSW 2052, Australia*

## HIGHLIGHTS

- A reconfigurable dissipativity-based distributed MPC approach is developed.
- The control system reconfigures itself based on the changing process topology.
- Dynamic supply rates are used to render the control design less conservative.
- The supply rates are linearly parameterized by the process network structure.

## ARTICLE INFO

*Article history:*
Received 1 November 2014
Received in revised form
17 December 2014
Accepted 16 January 2015
Available online 24 January 2015

*Keywords:*
Plantwide control
Reconfigurable distributed control
Distributed model predictive control
Dissipativity
Process network topology
Flexible manufacturing

## ABSTRACT

An approach to reconfigurable distributed model predictive control based on reconfigurable controller dissipativity properties is developed. The dissipativity properties of the controllers are updated online to reconfigure themselves for changes in the process network topology, which may be due to changing product specifications, feedstock type or scheduled or unscheduled maintenance; allowing for more flexible and agile manufacturing processes. The use of dissipative systems theory allows for the interaction effects between individual processes to be taken into account in control design to achieve high levels of plant-wide performance. Plant-wide performance and stability bounds are developed based on dissipative systems theory, which in turn are translated into the dissipative trajectory conditions on each local controller. This approach is enabled by the use of dynamic supply rates in quadratic difference form parameterised as linear functions of the process network structure.

## 1. Introduction

Model predictive control (MPC) is one of the most successful modern control techniques currently in use in the chemical industry (Qin and Badgwell, 2003). Key strengths of MPC in this application are its ability to explicitly handle hard and soft constraints and to generate an optimal control sequence. Additionally, the scale of plant-wide process control problems and the strong interactions between unit processes present significant challenges in control practice. Heat integration and material recycle are common in modern chemical plants, often to optimize steady state efficiency, rather than dynamic operability. These recycle streams, which may be implemented at both the unit and plant-wide level, represent positive feedback loops which can harm control performance. The complexity of process networks means that a centralized control structures are often not practical. The characteristics of modern chemical plants as described above, and the computational load required for plant-wide MPC suggest that a distributed control approach is appropriate in these situations, for example in Dunbar (2007) it is shown that distributed MPC yields superior performance to decentralized MPC.

In distributed MPC (DMPC) controllers local to each process unit communicate with one another to improve predictions and global performance whilst distributing the computational load. However, the coordination of these local controllers is still a challenging problem. Rawlings and Stewart (2008) showed that modeling interactions and exchanging trajectories alone are not sufficient to ensure plant-wide stability in DMPC schemes. Common techniques for ensuring MPC stability based on terminal constraints and terminal costs (for example Maciejowski, 2002; Mayne et al., 2000) cannot be used to ensure plant-wide stability as the effects of interconnections and interactions between subsystems are not taken into account. As such, it is necessary to implement plant-wide stability conditions in DMPC applications.

---

* Corresponding author.
*E-mail address:* j.bao@unsw.edu.au (J. Bao).

http://dx.doi.org/10.1016/j.ces.2015.01.040

Many recent developments have focused on cooperative distributed MPC approaches, where the controllers communicate information to solve the global optimization problem in their local manipulated variables. This is in contrast with non-cooperative DMPC, in which case the controllers optimize their local cost functions. It has been found that the Pareto optimal solution can be obtained if controllers iterate to convergence and that closed-loop stability may be assured when the communication iteration is terminated before convergence (Stewart et al., 2010b). This has been extended by introducing a technique to decrease computational overheads (Stewart et al., 2010a). In Jia and Krogh (2001), a constraint is placed on the state at the next time step so as to ensure that stability is maintained when short prediction horizons are used. A technique known as *Lyapunov MPC* has been developed to provide a framework for ensuring stability of DMPC schemes(Liu et al., 2008, 2009). This framework has since been extended to allow for iterative and sequential schemes (Liu et al., 2010), and asynchronous and delayed measurements (Liu et al., 2012). A detailed description of this framework is given in Christofides et al. (2011).

This paper builds upon the analysis in our previous work (Tippett and Bao, 2013, 2014) to consider the effect of changing process network topology on the analysis and dissipativity-based distributed MPC design, with a particular focus on facilitating flexible manufacturing operations by allowing the controllers to reconfigure themselves for changing process networks. This finds application in modern chemical plants where fixed equipment has its interconnection structure reconfigured or changed to produce different products/ product grades, or utilise multiple feedstocks. Such a problem is also known as flexible or holonic manufacturing (Chokshi and McFarlane, 2008b). Examples of such cases are presented in Wauters et al. (2012) in the context of food processing, Chacón et al. (2004) for oil production, Chokshi and McFarlane (2008a) for chemical process operations and Salomons et al. (2004) for processing methane emissions. Another application is to ensure the stability of the process network when some process units are taken offline for scheduled maintenance. Finally, the approach may allow for process operations to be continued in the case of unscheduled maintenance (i.e. failure of some process units). Additionally, there are applications of flexible manufacturing in the field of mechanical engineering. In the current paper, the dissipativity properties of the controllers are *parameterized* by the process network topology. Thus, the dissipativity properties (essentially the supply rates) of the controllers change with the process network topology, to allow the controllers to reconfigure. This is fundamentally different to our previous work where the controller dissipativity properties remained constant, and were 'robustified' to handle unknown changes in the controller communication network (due to communication failure or data loss) (Tippett and Bao, 2014). Knowledge of the current configuration of the process is a key difference between the proposed approach and many applications in the control of switched systems, where the current mode of the system is often unknown. An additional difference is that the framework presented in this paper allows for the parameter which defines the reconfigurations of the process to vary either discretely or continuously. Whereas in the switched systems literature it is often assumed that the process (and/or controller) has discrete switching modes.

A key motivation for flexible manufacturing is to make process operations more competitive by improving their agility, and to add value by providing mass customisation of speciality products (Shah, 2005). This is a significant step away from traditional continuous process operations which focused on steady state designs. However, there has been a recent trend towards flexible or 'smart' plants (Christofides et al., 2007), in which processing operations are integrated with business needs and more agile allowing for swiftly moving business needs to be met. In line with this trend there are recent developments in the process control literature in this area. For example, recent developments in distributed reconfigurable control by Chokshi and McFarlane are presented in Chokshi and McFarlane (2008b) based on holonic manufacturing and supply chain management. There it is argued that distributed, as opposed to more traditional hierarchical structures are more suited to reconfigurable control due to their increased flexibility.

Dissipativity is a useful tool for reconfigurable DMPC as it can capture the effect of interactions between unit processes on stability and performance for changing process network topologies. Additionally, the dissipativity properties of the process network can be determined as a *linear* combination of that of the individual process. This is particularly useful in the current work, where the process network changes to enable flexible manufacturing. Some applications of dissipative systems theory to the analysis and control of large-scale systems include Moylan and Hill (1978), Scorletti and Duc (2001), Ydstie (2008) and Vidyasagar (1981). Additionally, there are dissipativity based approaches to MPC for single systems in the recent literature. Robust MPC for systems with dissipative uncertainty has been studied (Løvaas et al., 2007, 2008). Whilst an MPC approach for passive nonlinear systems has been presented to ensure closed-loop stability (Raff et al., 2005). Chen and Scherer placed a dissipativity ensuring constraint on the online MPC algorithm, which guarantees minimum $\mathcal{H}_\infty$ performance (Chen and Scherer, 2004, 2006). In the authors previous work (Tippett and Bao, 2013), an approach to DMPC was developed in which a dissipativity ensuring constraint is imposed on each controller to ensure plant-wide stability and performance bounds.

The notation used in this paper is briefly introduced. $A > (\geq) 0$ for a symmetric matrix $A$, means that $A$ is positive definite (semidefinite). $\text{diag}(A_1, \ldots, A_n)$ denotes the formation of a block matrix with $i$th diagonal element being $A_i$. The forward shift operator is denoted by $\sigma$, that is, $\sigma^k x(t) = x(t+k)$. $\phi(\zeta, \eta) \in \mathbb{R}^{n \times m}(\zeta, \eta)$ denotes an $n \times m$ dimensional two variable polynomial matrix in the indeterminates $\zeta$ and $\eta$ with real coefficients. The degree of such a matrix, denoted by $\deg(\phi)$, is defined as the maximum power of $\zeta$ and $\eta$ appearing in any element of $\phi(\zeta, \eta)$. The set of the vertices of a hyperrectangle $H$ is denoted by vert $H$.

The remainder of this paper is structured as follows: in the following section some preliminary material on dissipative systems theory is presented to ensure that the paper remains self contained. In Section 3 the description of the process network and plant-wide dissipativity conditions, parameterized by the changing process network topology is formulated. Then, in Section 4 the design of the reconfigurable DMPC algorithm is presented, followed by the online algorithm. The paper is then concluded by an example and a discussion and some summarizing remarks.

## 2. Preliminaries

Dissipative systems theory was first formalized in Willems (1972a,b), as an extension of the concept of passive systems. Intuitively speaking, dissipative systems are those for which the increase in stored energy is bounded by the amount of energy supplied by the environment (here energy may refer to actual physical energy, or an energy-like quantity). This provides a useful framework for studying interconnected systems as it is an input–output property which allows for much of the complexity of the problem to be shifted to the interconnection relations, rather than studying centralized process models. A discrete time dynamical system with input, output and state