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Partitioning for distributed model predictive control of nonlinear processes

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ABSTRACT

A distributed model predictive control (DMPC) strategy brings interesting features of topology, flexibility and maintenance to large-scale nonlinear systems. This work presents contributions in the study of distributed controllers for nonlinear and large-scale systems. Two types of distributed predictive control based on model (DMPC) are proposed: non-cooperative locally linearized DMPC and cooperative locally linearized DMPC. The decomposition is performed based on a local linearized version of the process model by using local matrices representing interactions between controlled outputs, states and inputs. The proposed strategy was successfully evaluated and compared to the centralized control strategy.

1. Introduction

The most basic requirement of a control system is that it guarantees closed-loop stability while increasing the overall process efficiency. With the great development of system analysis tools, inexpensive computer power and data for modeling and developing process identification, it is possible today to address large and complex systems in a systematic framework.

As computational numerical algorithms and computer power evolve, the type and size of potential applications also broadens. Problems that previously were considered intractable, from a computational point of view, now are solvable. However, in order to well understand the full potential of large-scale systems, especially in process control, is necessary to specify how a large-scale system is defined. A large-scale system has many different meanings in the literature. It can be used to define a system if it can be partitioned into subsystems. Of course one has to be reasonable about dimensions, otherwise a simple decomposition of a low dimensional system could be misused for large-scale system. A decomposed system can be structured as an interconnected system or as a hierarchically structured system requiring a coordinator.

Control of large-scale systems (LSS) has been long studied, particularly the issue of how to distribute control tasks in a complex large-scale process (Mesarovic et al., 2000; Sandell et al., 1978). The control of LSS requires coordination of all existing interactions among the constituent subsystems. Subsystems of a plant are usually designed independently or are added later as the installed plant evolves. These changes are usually motivated by production requirements or environmental regulations. Most LSS utilize decentralized control as the strategy of choice. However, for subsystems with strong interactions, this approach can lead to unacceptable performance. Centralized control is able to address optimally the problem of interaction, but with high structural and organizational costs, making the complex structure and the upgrade maintenance costly.

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Centralized and decentralized control are the two design extremes for the control of large-scale systems. While centralized control takes into account all possible interactions, decentralized control ignores them partially or completely. Additionally, both decentralized and centralized control require no communication between subsystems. An alternative control structure is needed, therefore, that does not have the organizational and maintenance costs of centralized control, but could give acceptable performance in large-scale, highly interacting systems.

An alternative to centralized control that preserves the topology and flexibility of decentralized control and at the same time may offer a nominal closed-loop stability guarantee is the distributed control approach. In this control structure, the interactions between subsystems are modeled and information between the subsystems is shared between them. Ignoring the structural constraints and addressing the control problem as a distributed optimization problem may lead to an unsuccessful industrial application, where it is desired high flexibility on the use of existing control structure (Rawlings and Stewart, 2008).

In order to design a controller that is able to address the issues noted above one needs to consider the following:

Partitioning How can one decompose a LSS into subsystems with known properties to address the structural coupling in the plantwide control problem?

Communication How can one design a distributed model-based control architecture by knowing the subsystems from the partitioning step above in a way of not having either a large communication burden not a large closed-loop deterioration behavior when compared to a centralized performance?

Performance How to evaluate the global properties of the distributed model based control law based on the set of subsystems?

Another important definition is the concept of complexity. A system is called complex if conventional system analysis techniques result in poor solution. A large-scale system is complex. There is also the definition based on the centrality concept. A system is of large-scale if it is not formed by subsystems grouped into a single center. There are also additional concepts such as: (a) System of System concept (SoS): it is a class of complex systems whose constituents are themselves complex. As defined by Jamshidi (2008), it is a metasystem that is comprised of multiple autonomous embedded complex systems that can be diverse in technology, context, operation, geography and conceptual frame; (b) the Enterprise Systems of Systems Engineering (SoSE) that is focused on coupling traditional systems engineering activities with enterprise activities of strategic planning and investment analysis (Carlock and Fenton, 2001), and (c) Ultra-large-scale system (ULSS): it is used in Computer Science and Software Engineering to refer to software intensive systems (Feiler et al., 2006).

Even though the above presented concepts are not universally accepted, in case of distributed process control, we are mostly interested to address standard LSS, but it can be also applied to more general systems, such as SoS. Due to the fact that one may have systems of interest of very high dimension, which are complex in nature and even might not be central at times. Therefore, because of the LSS broad range of understanding, it can be used to define systems in many different fields, such as electric power system networks, water distribution systems, manufacturing systems, communication networks and economy and management systems. In this work, we are mostly concerned with the process control view of large-scale system for distributed model predictive control.

There are three classes of models in LSS: (a) aggregated models, where a higher dimensional system is reduced by approximation to a lower dimensional system. In this case the major properties such as controllability, stability and so forth must be preserved from the original system to the reduced one; (b) perturbed models, where the reduced model neglects existing interactions in the original model by using a regular or singular approach for weak and strong coupling, respectively, and finally, (c) descriptive variable models, in which the system representation consists mainly of physical or economical variables of the system (Jamshidi, 1997). A classification of the LSS approaches can be also made according to the topology of the communication network, the different communication protocols used by the local controllers, and the cost function considered in the local controller optimization problem (Christofides et al., 2013).

Decomposition for distributed optimization has been widely used in the literature for process optimization and distributed control. Despite all of the existing research, for general problems, there is no systematic method for determining an optimal decomposition. The existing methodologies are based on: a case by case study aiming to use any special structure available to partition the system, or by using a simulation study to create blocks with small exogenous interaction; use of network science theory, such as the community detection strategy (Tang et al., 2018), to seek a strict block diagonal or block triangular structure by using network algorithms. There are two major aspects to note, either the existing methodology does not apply to a general system description, or it is based on a network distributed optimization that does not guarantee performance. The study of distributed optimization algorithms is still an open problem of research.

A communication-based MPC (Model Predictive Control) scheme was investigated by Jia and Krogh (2002) and DMPC and estimation problems are considered in Mercangöz and Doyle III (2007) for square plants perturbed by noise. Motee and Sayyar-Rodsari (2003) introduced a partitioning algorithm that uses an open-loop performance metric to partition the distributed system into subsystems balancing them against the closed-loop cost of the control actions for the overall distributed system. In Venkat et al. (2005), the authors proposed a DMPC algorithm designed for linear systems based on a process of negotiations among DMPC agents. Zhang and Wang (2012) presented a strategy for linear time invariant systems that requires decomposing the entire system into subsystems based on the control input distribution. This method, however, cannot be directly applied if the system has inputs affecting all states of the system. Zhang et al. (2013) proposed a DMPC algorithm for input-saturated polytopic uncertain systems. The subsystem controllers are obtained by optimizing a global cost function and acite min-max distributed MPC strategy was proposed for uncertain distributed systems.

It is known that linear systems are almost nonexistent in nature, but around the operating point of a system one can make use of the linearized model to predict the process behavior without significant loss in performance of the control system. LMPC (Linear Model Predictive Control) can be applied to these types of problems, where the goal is to operate them in a region around a steady-state. Some processes with a high degree of non-linearity may require the implementation of a nonlinear MPC approach (NMPC). The principle that