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Coalitional model predictive control of an irrigation canal

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ABSTRACT

We present a hierarchical control scheme for large-scale systems whose components can exchange information through a data network. The main goal of the supervisory layer is to find the best compromise between control performance and communicational costs by actively modifying the network topology. The actions taken at the supervisory layer alter the control agents' knowledge of the complete system, and the set of agents with which they can communicate. Each group of linked subsystems, or *coalition*, is independently controlled through a decentralized model predictive control (MPC) scheme, managed at the bottom layer. Hard constraints on the inputs are imposed, while soft constraints on the states are considered to avoid feasibility issues. The performance of the proposed control scheme is validated on a model of the Dez irrigation canal, implemented on the accurate simulator for water systems SOBEK. Finally, the results are compared with those obtained using a centralized MPC controller.

1. Introduction

The progress made in data networks technology and the derived decreasing implementation costs—to which wireless networks have hugely contributed—have enabled the application of advanced control techniques in systems where the high cost of communication was a substantial obstacle. In particular, large scale systems related with public infrastructures are now fully within the scope of real-time control engineering, fostering the potential of a positive impact on the fundamental services provided countrywide [1].

This paper deals with water management in irrigation canals, a demanding task which entails finding the right trade-off among different sectors in direct competition (agricultural, municipal, and industrial). Since irrigated agriculture constitutes the largest consumer of freshwater resources, the modernization of canal operational management could drastically improve water conservation efficiency and supply flexibility. Moving in this direction, several advanced control strategies have been proposed over the last decades (see, e.g., the survey [2] and references therein). In [3], an optimal quadratic criteria is used to adjust the parameters of downstream level feedback controllers. Different classes of controllers are considered, ranging from PI controllers at each gate to a centralized controller. The improvement derived from the communication of control actions among neighboring pools is also investigated. In [4], the effectiveness of model predictive control in water systems is studied and compared to classical feedback and feedforward strategies.

Among several challenging aspects regarding irrigation systems, geographical distance is one of the most interesting. Water networks are generally very disperse, and often different parts of the system are owned by independent entities, expectedly unwilling to coordinate their control actions unless strictly necessary. Moreover, permanent communication between the various parts of the network can be impractical. Consequently, the use of a traditional centralized control approach is hampered, even when the water network is owned and managed by a single entity. Considering all these factors, distributed control schemes can provide solutions able to satisfy the different actors involved. Thus, irrigation canals have become a popular benchmark to assess the performance of hierarchical and distributed control schemes. In [5], a thorough classification of these is given. A survey of centralized and distributed MPC schemes for water systems is provided in [6]. In this same work, the potential of the application of a distributed MPC scheme—based on an augmented Lagrangian formulation—is investigated with a simulation study on an irrigation canal. Also based on an augmented Lagrangian formulation, the work of [7] describes the decomposition of the receding-horizon optimal control problem for heterogeneous irrigation systems, aimed to reduce the computational complexity and to conform to the system topology. The performance objective considered in [7] accounts for

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the costs of water pumping and water losses, and the profits from power generation. A two-layer control scheme is proposed in [8], where the top layer follows a risk management strategy to cope with unexpected changes in the demand, failures or additional maintenance costs, and the bottom layer optimizes the values of water flows by means of a distributed MPC technique. A section of an irrigation canal located in Spain is considered as case study.

The idea behind these solutions is to partition the centralized problem among a given number of local controllers or *agents* (see, e.g., [9]). Depending on the degree of dynamic interaction between the subsystems, the controllers are categorized in the literature either as distributed or as decentralized. In the first class the agents need to communicate to coordinate their operations [10–13]. By contrast, in the second class the limited degree of interaction allows the agents to tackle their control tasks with no need of communication [14,15]. Between these two classes lie the *coalitional* control schemes. In these, the control strategy is adapted to the varying coupling conditions between different parts of the system, promoting cooperation among the control agents most concerned at any given time. The formation of groups of cooperative agents based on the active coupling constraints is considered in [16]. The work of [17] describes a hierarchical framework where information among the agents is exchanged at each time step within clusters of strongly dynamically coupled subsystems, while a slower communication rate is required between different clusters. In [18], the complexity of the model predictive control problem of the Barcelona drinking water network is reduced by means of a partitioning algorithm, in order to control in a hierarchical-distributed manner the resulting subnetworks. In [19] a flexible hierarchical MPC scheme is proposed for a hydro-power valley, where the priority of the agents in optimizing their control actions can be rearranged according to the different operational conditions.

The present work focuses on how the interaction between the subsystems varies with time. Consider a large-scale system with an associated network, in which a number of control agents communicate in order to derive their knowledge of the overall system. Here, a two-layer hierarchical control strategy that manipulates the network topology with regard to both the current state of the system and the communicational cost is proposed. Those data links that do not yield a significant improvement of the control performance, compared with their relative cost of use, are disconnected. This feature is interesting, e.g., for communication infrastructures based on battery-powered wireless communication devices. Thus, any agent will be able to communicate only with those agents whose cooperation is most relevant, and the overall system will be partitioned into *coalitions* working in a decentralized fashion.

The properties of a multi-agent control scheme based on this idea are discussed in [20], where the time-variant relevance of the communication within a set of dynamically coupled, unconstrained linear systems is analyzed using tools from cooperative game theory [21]. The research was extended towards input constrained systems in a preliminary version of this work [22], employing a model predictive control strategy [23,24] at the bottom layer. A local Luenberger observer was used within each coalition in order to estimate the dynamic influence caused by external subsystems.

In this article, constraints on both states and inputs are considered, and local Kalman filters are used to estimate the dynamic couplings between different coalitions, viewed as perturbations. Information about any measurable disturbance can be now employed at the bottom layer. The proposed control scheme is validated on a detailed model of a 45 km section of the Dez irrigation canal, implemented on the SOBEK hydrodynamic simulator. For comparison, the results are shown along with those obtained using a centralized MPC controller.

The paper is organized as follows. In Section 2, a formulation of the control problem is presented. The new distributed control algorithm is introduced in Section 3. The performance of the controller is finally validated in Section 4, employing a model of a section of the Dez irrigation canal as case study.

2. Problem formulation

2.1. System model

On the basis of the work of [4], where the implementation of model-based control techniques on water systems has been examined, a discrete-time linear approximation of the dynamics of the irrigation canal, namely the ID model [25], is adopted here. According to this model, each reach is characterized as a transport delay in series with an integrator.[1] A minimal order representation of the dynamics of the canal follows, which is suitable for the application to the control scheme presented in this article, where the computational burden is a major issue.

The canal is partitioned into its essential components, i.e., pairs composed by a gate (the actuator) and its downstream reach, forming a set $\mathcal{V} = \{1, \ldots, N\}$ of subsystems. The dynamics of any subsystem $i \in \mathcal{V}$ are described by the linear model:

$$x_i(k+1) = A_{ii}x_i(k) + B_{ii}u_i(k) + E_i p_i(k) + G_i w_i(k) \quad (1a)$$

$$w_i(k) = \sum_{j \in \mathcal{N}_i} A_{ij}x_j(k) + B_{ij}u_j(k) \quad (1b)$$

where $x_i \in \mathbb{R}^{n_i}$ and $u_i \in \mathbb{R}^{m_i}$ are the state and input vectors respectively, $p_i \in \mathbb{R}^{l_i}$ is a measurable perturbation due to the offtake flow, and $w_i \in \mathbb{R}^{r_i}$ describes the influence on x_i of the neighbors' states and inputs. In (1b), $x_j \in \mathbb{R}^{n_j}$ and $u_j \in \mathbb{R}^{m_j}$ are the state and input vectors of each neighbor $j \in \mathcal{N}_i$ of subsystem i. The neighborhood set $\mathcal{N}_i$ is defined as:

$$\mathcal{N}_i = \left\{ j \in \mathcal{V} | A_{ij} \neq \mathbf{0} \vee B_{ij} \neq \mathbf{0}, j \neq i \right\} \quad (2)$$

i.e., it is the set composed by any subsystem $j \neq i$ whose state and/or input produce some effect on the dynamics of subsystem i.

Remark 1. Even if model (1) is tailored to the case study, it is indeed a general formulation fitting a wide variety of large-scale systems.

The state vector

$$x_i(k) \equiv [q_i(k-1), \ldots, q_i(k-d_i), e_i(k)]^\top$$

gathers information about the flow q_i along the reach and the water level error e_i with respect to a desired value. Notice that an augmented representation is used in order to take into account the flow transport delay d_i. The input $u_i(k) \equiv \Delta q_i(k)$ is the variation of the flow entering the reach i, controlled at its upstream gate.

For each subsystem, the measure of the water level error $e_i(k)$ in the backwater section of the reach is available to its control agent; the rest of the state variables (water flow in different sections of the reach) are observable.

2.2. Exchange of information

All the control agents can communicate through a data network whose topology is described by means of the undirected graph $\mathcal{G} = (\mathcal{V}, \Lambda)$, where to each subsystem in $\mathcal{V}$ is assigned a node. Let $\mathcal{L} \subseteq \mathcal{V} \times$

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[1] A more detailed description of the model and the parameters of the canal is given in Section 4.