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Reliable fault-tolerant model predictive control of drinking water transport networks

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ABSTRACT

This paper proposes a reliable fault-tolerant model predictive control applied to drinking water transport networks. After a fault has occurred, the predictive controller should be redesigned to cope with the fault effect. Before starting to apply the fault-tolerant control strategy, it should be evaluated whether the predictive controller will be able to continue operating after the fault appearance. This is done by means of a structural analysis to determine loss of controllability after the fault complemented with feasibility analysis of the optimization problem related to the predictive controller design, so as to consider the fault effect in actuator constraints. Moreover, by evaluating the admissibility of the different actuator-fault configurations, critical actuators regarding fault tolerance can be identified considering structural, feasibility, performance and reliability analyses. On the other hand, the proposed approach allows a degradation analysis of the system to be performed. As a result of these analyses, the predictive controller design can be modified by adapting constraints such that the best achievable performance with some pre-established level of reliability will be achieved. The proposed approach is tested on the Barcelona drinking water transport network.

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1. Introduction

Potable water is provided to consumers and industry by means of drinking water networks, which are large-scale systems that can be structurally organized in several layers (Ocampo-Martinez, Puig, Cembrano, & Quevedo, 2013):

- A supply layer, composed of water sources, large reservoirs and natural aquifers.
- A transportation layer, linking water treatment and desalination plants with reservoirs distributed all over a city.
- A distribution layer, used to meet consumer demands and link reservoirs with consumers.

This paper is focused on the transportation layer and, in particular, on drinking water transport networks (DWTNs). These networks require sophisticated supervisory-control strategies to ensure and maintain optimal performance even in faulty conditions. In order to take advantage of these expensive infrastructures, also necessary is a highly sophisticated real-time control (RTC) scheme to ensure optimal performance (Brdys & Ulanicki, 1994; Ocampo-Martinez et al., 2013). The RTC scheme in a DWTN might be local or global. When control is local, regulation devices only use measurements taken at specific locations. While this control structure is applicable in many simple cases, it may not be the most efficient option for large systems with a highly interconnected and complex sensor and actuator infrastructure. A global control strategy, in contrast, which computes control actions taking into account real-time measurements all through the network, is likely the best way to use infrastructure capacity and all available sensor information. Global RTC deals with the problem of generating control strategies (ahead of time), based on a predictive dynamic model and telemetry readings of the network to optimize operation (Ocampo-Martinez et al., 2013). The multivariable and large-scale nature of DWTNs have led to the use of some variants of model predictive control (MPC) as a global control strategy (Pascual et al., 2013).

Global RTC of DWTNs needs to be operative even in faulty conditions. This problem calls for the use of fault-tolerant control (FTC) mechanisms after a fault is diagnosed so as to avoid the global RTC stopping every time a fault appears. FTC was developed in order to address the growing demand for plant availability (Blanke, Kinnaert, Lunze, & Staroswiecki, 2016). The aim of FTC is

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to keep a plant fully operative by designing its control system such that system performance can be kept close to desirable levels and stability conditions can be maintained, not only when the system is in nominal conditions but also in the presence of system component faults; FTC should, at the very least, ensure acceptable degraded performance (Noura, Theilliol, Ponsart, & Chamssedine, 2009). Tolerance against faults can be embedded in MPC relatively easily in several different ways, as discussed in Maciejowski (2002):

- Changing the constraints in order to represent the fault effect, with the algorithms for actuator faults being especially easy to adapt.
- Modifying the internal plant model used by the MPC in order to reflect fault influence on the plant.
- Relaxing the nominal control objectives in order to reflect system limitations under faulty conditions.

Reviewing the literature, the inclusion of fault tolerance in MPC has already been considered by several authors, including Zhang and Jiang (2008), who provide a detailed review of the state-of-the-art in FTC. Camacho, Alamo, and Muñoz de la Peña (2010) provide a general overview on how fault tolerance can be embedded in MPC. The inclusion of fault-tolerance in MPC has mainly been addressed by considering practical strategies according to the application domain. For example, Prodan, Zico, and Stoican (2015) described a method for including fault tolerance in MPC for smart grids in order to ensure the proper amount of energy in storage devices and reliable coverage of essential consumer demand. Ocampo-Martinez and Puig (2009) applied fault tolerance in MPC to sewage networks considering a hybrid systems framework. Yang and Maciejowski (2012) designed a group of predictive controllers to compensate for the fault effects for each component in a wind turbine. More theoretical aspects have also begun to be studied, such as coupling with active fault diagnosis (Raimondo, Marseglia, Braatz, & Scott, 2013) and the use of set-invariance theory (Yetendje, Seron, & Doná, 2012). More recent additional objectives for MPC controllers, proposed in Sanchez, Escobet, and Puig (2015) and Salazar, Weber, Sarrate, Theilliol, and Nejari (2015), have been to preserve system health and reliability, respectively.

The research presented in this paper is based on three concepts:

- How fault accommodation/reconfiguration strategies were applied in a linear quadratic regulator (LQR) (Staroswiecki & Berdjag, 2010).
- The idea that fault configurations should be evaluated before applying FTC strategies (Staroswiecki, Commault, & Dion, 2012).
- The idea of using reliability with the FTC design (Guenab, Weber, Theilliol, & Zhang, 2011).

Starting from these key ideas, we propose a new reliable fault-tolerant MPC scheme for application to DWTNs. After a fault has occurred, the MPC controller should be redesigned to cope with the fault by considering either a reconfiguration or an accommodation strategy, depending on knowledge available on the fault. Before starting to apply the FTC strategy, whether the MPC controller will be able to continue operating after the fault appears should be evaluated. This is done in two ways: first, a structural analysis is done to determine the level of loss in post-fault controllability; second, a feasibility analysis is done of the optimization problem related to the MPC design so as to consider the fault effect on actuator constraints. By evaluating the admissibility of different actuator-fault configurations (AFCs), critical actuators regarding fault tolerance can be identified considering structural, feasibility, performance and reliability analyses. This has been studied in Robles, Puig, Ocampo-Martinez, and Garza (2012), where only some of the analyses proposed here were considered.

Our approach allows a degradation analysis of the system to be performed in terms of performance and reliability. As a result of this analysis, the MPC controller design can be modified, adapting the constraints so as to achieve the best achievable performance with some pre-established level of reliability. The proposed approach was tested in the Barcelona DWTN, in an application that also shows the relevant information about critical actuators can be extracted by considering the different analyses we propose.

The main contribution of this paper is the design of methodologies for the analysis of the influence of faults taking into account reliability features. As discussed, some of the proposed methodologies have been previously documented but not their application in the considered fault tolerance framework, to the best of our knowledge, after a thorough literature review (a secondary contribution of the paper).

The remainder of the paper is organized as follows. MPC controller design for DTWNs to include fault tolerance is introduced in Section 2. Section 3 describes the proposed fault tolerance evaluation approach for the MPC controller after fault occurrence. Section 4 deeply describes the design of the MPC controller such as the reliability can be preserved. The results of an application of this approach to the Barcelona DWTN are provided in Section 5. Finally, Section 6 concludes with some suggestions for further research.

2. MPC of DWTN with fault-tolerant capabilities

2.1. Flow-based control-oriented model

This paper considers a general DWTN as represented by a digraph $G(\mathcal{V}, \mathcal{E})$ (see Šiljak, 1991 for more details), where a set of elements, i.e., n_s sources, n_x storage elements, n_q intersection nodes, and n_d sinks, are represented by $v \in \mathcal{V}$ vertices connected by $a \in \mathcal{E}$ links. Due to the network function, water is transported along the links by n_u flow actuators (i.e., pipes and valves), passing through reservoirs or tanks, from specific origin locations to specific destination locations. The network is subject to several capacity and operational constraints, and to measured stochastic flows to customer sinks as driven by water demand.

Selecting the volume in storage elements as the state variable $x \in \mathbb{R}^{n_x}$, the flow through the actuators as the manipulated inputs $u \in \mathbb{R}^{n_u}$, and the demanded flow as *additive* measured disturbances $d \in \mathbb{R}^{n_d}$, the control-oriented model of the DWTN may be described by the following set of linear (or linearized) discrete-time difference-algebraic equations (DAE) for all time instants $k \in \mathbb{N}$:

$$x_{k+1} = Ax_k + Bu_k + B_d d_k, \tag{1a}$$

$$0 = E_u u_k + E_d d_k, \tag{1b}$$

where the difference equation in (1a) describes the dynamics of the storage tanks, and the algebraic equation in (1b) describes static relations in the network (i.e., mass balance at junction nodes). Moreover, A, B, B_d, E_u and E_d are time-invariant matrices of suitable dimensions as dictated by the network topology.

System (1) is subject to hard state and input polytopic constraints given by:

$$\mathbb{U} \triangleq \left\{ u \in \mathbb{R}^{n_u} \mid u_{\min} \le u \le u_{\max} \right\}, \tag{2a}$$

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