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Formal controller synthesis for wastewater systems with signal temporal logic constraints: The Barcelona case study

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ABSTRACT

We present an approach for formal controller synthesis of the Barcelona wastewater system. The goal of the controller is to minimize overflow in the system and to reduce environmental contamination (pollution). Due to the influence of sudden and unpredictable weather changes within the Mediterranean climate, we propose robust model predictive control strategy. This approach synthesizes control inputs (i.e., flows through network actuators) that make the system robust to uncertainties in the weather forecast; control inputs are updated in an online fashion to incorporate the newly available measurements from the system and the disturbances. We employ signal temporal logic as a formal mechanism to express the desired behavior of the system. The quantitative semantics of the logic is then used to encode the desired behavior in both the set of constraints and the objective function of the optimization problem. We propose a solution approach for the obtained worst-case optimization, which is based on transforming the nonlinear dynamics of the system into a mixed logical dynamical model. Then, we employ Monte Carlo sampling and dual reformulation to get a mixed integer linear or quadratic programming problem.The proposed approach is applied to a catchment of the Barcelona wastewater system to illustrate its effectiveness.

1. Introduction

The infrastructure for water and wastewater management is being continuously upgraded due to the constant increase in demand for water and wastewater services as a result of population growth. In order to support this upgrade, the water industry has been investigating the potential benefits of using more advanced automatic control strategies. The design and automatic control of sewer networks pose new challenges to the control community. The newly designed methodologies should be able to handle the effect of uncertainties in the amount of precipitation, the physical and operational constraints of the network, and the effects of delays and nonlinearities in the dynamics of the system. These challenges require improving performance of the traditional control strategies such as on-off and PID controllers, which are not capable of handling such issues. Model predictive control (MPC) seems to be a suitable methodology to control sewer networks as it can deal with these particular challenges associated with such systems. MPC is an online control technique that uses a mathematical model of the considered system to compute the control inputs by minimizing a cost function [1–4]. Moreover, it is capable of incorporating either linear or nonlinear dynamics of the system as well as handling constraints on inputs, states and outputs. Hence, the MPC methodology is quite suitable for the global control of urban sewage systems within a hierarchical control structure [5,6].

The system under investigation in this paper is part of the Barcelona wastewater system, which is subject to sudden weather-change events within the Mediterranean climate. We consider the Barcelona test catchment (BTC) that covers a surface area of 22.6 km^2 and represents all the typical elements of the whole network. The application of deterministic MPC to Barcelona wastewater system has been investigated in [7] for a portion of this system and its benefits have been examined toward the potential percentage reductions in both flooding and pollution in Barcelona sewage network. In this paper, we build on the work of [7] by including uncertainty in the amount of precipitation as a bounded

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disturbance and by formulating a robust MPC optimization problem [8–12] to synthesize control inputs.

In order to specify the desired behavior of a system with continuous dynamics, signal temporal logic (STL) is one of the most useful languages. In comparison with other temporal logic formalisms, STL has the advantage of naturally admitting a quantitative semantics. As such, in addition to the binary answer to the satisfaction question of the specifications, it provides a real number that indicates the extent to which the specification is either satisfied or violated. This quantitative semantics associated to the STL specification is referred to as the *robustness function*. Incorporating such temporal specification in the optimization problem formulation enforces the closed-loop system to satisfy the desired temporal behavior, as it is confirmed by the simulation results of this paper.

Considering the nonlinear (or hybrid) nature of the network model, we show that the proposed robust MPC optimization problem can be formulated as mixed integer linear or quadratic programming (MILP or MIQP) problems as follows. First, the nonlinear dynamics of the wastewater network are transformed into a mixed logical dynamical (MLD) model. Then, the nonlinear expressions in the objective function and the STL constraints are transformed into mixed integer linear terms and constraints, respectively. Finally, we employ either dual reformulation or Monte Carlo method in the inner optimization problem, i.e., the maximization problem, to get either an MIQP problem or an MILP problem. In the case of MIQP, we obtain a non-convex optimization problem, which we solve iteratively by linear approximation of the quadratic objective function. In the simulation results, we compare the performance of the dual reformulation with the Monte Carlo approach and we show the effect of STL specifications on system behavior.

1.1. Related work

STL has been used for controller synthesis in a variety of domains for uncertain systems using receding horizon control techniques [13–15]. Transforming STL constraints into mixed integer linear constraints has been used in [16]. Several works related to this wastewater system consider different models and cope with the design of alternative MPC approaches, e.g., [17,18] and references therein. Recent works have proposed different approaches for handling uncertainties in process control. The work reported in [19] proposes a two-level method to first estimate the worst-case disturbance profile using an uncertain finite impulse response (FIR) model. This profile is then employed to simulate the closed-loop nonlinear dynamic process model for obtaining the worst-case output variability and checking the feasibility of constraints. Likewise, the work reported in [20] proposes an MPC strategy that relies on nonlinear optimizations. This approach incorporates integer variables towards performing a modeling selection within the control structure. In our previous work [21], we studied a small part of BTC with only 3 tanks. In the current paper, we consider the full model of BTC, as presented in [7], to show that our method is both scalable and efficient for formally synthesizing control inputs for the system.

Our work is distinct from the previous works on wastewater systems in (a) considering uncertainty in the amount of precipitation both in the model and in the controller design; (b) employing STL to encode desired properties of the closed-loop trajectories; (c) proposing an approximate solution for the formulated optimization problem that is scalable and can be applied to the large dimensional model of the BTC.

The remainder of this paper is organized as follows. In Section 2, the considered model of the BTC is described. In Section 3, the robust MPC formulation is presented together with the constraints induced by both the model of the system and the STL specifications. In Section 4, we discuss the MLD model of the system and propose solution approaches to solve the mixed integer robust MPC optimization problem. In Section 5, the proposed control approach is applied to the BTC and the main results are proposed and discussed. Finally, Section 6 draws the main conclusions of the paper and the possible lines of future research. In order to keep the discussion of the paper focused, we summarize STL semantics and the notion of robustness in the appendices.

2. Barcelona test catchment model

We consider a portion of the sewer network of Barcelona that is representative, as it exhibits the main phenomena and the most common characteristics found in the entire network. The network consists of nine tanks, four control inputs corresponding to the manipulated flows, and eleven measured disturbances corresponding to the measurements of rain precipitation. Two wastewater treatment plants (WWTP) are used to treat the sewage before it is released to the receiving environment. Fig. 1 shows the part of Barcelona test catchment (BTC) area considered in this paper. There are two types of tanks in the model: one *real* tank (T_3), and eight *virtual* tanks (all tanks except T_3). The BTC has six weir overflow devices R_i, $i \in \{1, 2, \ldots, 6\}$, three redirection gates, one retention gate, and five T-pipes.

2.1. Description of the components

A virtual tank is a storage element that represents the total volume of sewage inside the sewer mains associated with a determined sub-catchment [22]. A real tank is a buffer that stores the wastewater and allows to redirect it towards different pipes in the network. Redirection gates are used to change the direction of the sewage while retention gates are used to retain the sewage flow at a certain point in the network. Weir overflow devices are used to specify the desired direction of the flow while taking into account the capacity of the pipes.

The role of T-pipes is to merge or split the sewage flows (Fig. 2). The equations of flow inside T-pipes at time step $k \in \mathbb{Z}_+$ can be written as $q_i(k) = q_{c,i}(k) + q_{f,i}(k)$ with

$$q_{c,i}(k) = \begin{cases} q_i(k) - \bar{q}_i, & q_i(k) \geq \bar{q}_i \\ 0, & q_i(k) < \bar{q}_i \end{cases} \quad \text{for} \quad i = 1, \ldots, 5, \tag{1}$$

where $\bar{q}_i$ denotes the maximum flow through pipe i. The outflows from redirection gates satisfy the mass conservation equation $q_i = q_{C_j,\text{in}} - q_{ui}$, where $q_{C_j,\text{in}}$ is the inflow to the redirection gate C_j, $j = 1, 2, 3$. Moreover, the outflow of the virtual tank i is proportional to the tank volume, i.e., $q_{x_i}(k) = \beta_i x_i(k)$ with β_i denoting the volume/flow conversion coefficient and $x_i(k)$ denoting the volume of tank T_i at time step k.

The flow equations in the weir overflow devices R_i, $i \in \{1, \ldots, 6\}$, can be defined as

$$q_{R_i,\text{out}}(k) = \begin{cases} q_{R_i,\text{in}}(k), & q_{R_i,\text{in}}(k) \leq \bar{q}_{R_i} \\ \bar{q}_{R_i}, & q_{R_i,\text{in}}(k) > \bar{q}_{R_i} \end{cases} \quad \text{for} \quad i = 1, \ldots, 6, \tag{2}$$

where $q_{R_i,\text{in}}(k)$ denotes the sum of inflows entering weir overflow device R_i at time step k, $q_{R_i,\text{out}}(k)$ denotes the outflow from R_i in the *desired* direction, and $\bar{q}_{R_i}$ denotes the maximum capacity of the pipe in the desired direction. Accordingly, the flow equation of the weir overflow device R_i in the *undesired* direction can be obtained by $q_{R_i,\text{in}}(k) - q_{R_i,\text{out}}(k)$. For instance in the case of R_1 in Fig. 1, $q_{R_1,\text{out}} = q_{R16}$ is the outflow and $\bar{q}_{R_1} = \bar{q}_{R16}$. The undesired flow direction of R_1 is q_{R1}, which can be obtained as $q_{R1}(k) = q_{R_1,\text{in}}(k) - q_{R16}$, with $q_{R_1,\text{in}}(k) = q_{u_4}(k) + q_{9R1}(k) + q_{x_4}(k)$. Unlike the real tank T_3, a virtual