Environmental Modelling & Software 101 (2018) 10–22

Contents lists available at ScienceDirect

Environmental Modelling & Software

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

Uncertainty-aware demand management of water distribution networks in deregulated energy markets

P. Sopasakis [a, *], A.K. Sampathirao [b, 1], A. Bemporad [c], P. Patrinos [a, 2]

[a] KU Leuven, Department of Electrical Engineering (ESAT), STADIUS Center for Dynamical Systems, Signal Processing and Data Analytics & Optimization in Engineering (OPTEC), Kasteelpark Arenberg 10, 3001 Leuven, Belgium
[b] Technische Universität Berlin, Fachgebiet Regelungssysteme, Einsteinufer 17, D-10587 Berlin, Germany
[c] IMT School for Advanced Studies Lucca, Piazza San Ponziano 6, Lucca 55100, Italy

ARTICLE INFO

Article history:
Received 15 May 2017
Received in revised form
13 October 2017
Accepted 28 November 2017

Keywords:
Drinking water networks
Bid-based energy market
Stochastic model predictive control
Graphics processing units
Scenario trees
Open-source software

ABSTRACT

We present an open-source solution for the operational control of drinking water distribution networks which accounts for the inherent uncertainty in water demand and electricity prices in the day-ahead market of a volatile deregulated economy. As increasingly more energy markets adopt this trading scheme, the operation of drinking water networks requires uncertainty-aware control approaches that mitigate the effect of volatility and result in an economic and safe operation of the network that meets the consumers' need for uninterrupted water supply. We propose the use of scenario-based stochastic model predictive control: an advanced control methodology which comes at a considerable computation cost which is overcome by harnessing the parallelization capabilities of graphics processing units (GPUs) and using a massively parallelizable algorithm based on the accelerated proximal gradient method.

Software availability

Name of software: RapidNet.
Hardware required: CUDA-compliant GPU (tested on NVIDIA Tesla 2075).
Software required: CUDA framework v6.0 or higher (including cuBLAS) and rapidjson (http://rapidjson.org/).
Availability: Open-source software, licence: GNU LGPL v3.0. Available online at https://github.com/GPUEngineering/RapidNet.
Program language: CUDA-C++/C++.
First release: 2017

1. Introduction

1.1. State of the art

The explosive proliferation of interconnected sensing, computing and communication devices has marked the advent of the concept of *cyber-physical systems* — ensembles of computational and physical components. In drinking water networks this trend has ushered in new control paradigms where the profusion of data, produced by a network of sensors and stored in a database, is used to prescribe informed control actions (Eggimann et al., 2017; Meseguer and Quevedo, 2017; Solomatine, 2003; Lobbrecht and Solomatine, 2002). Nevertheless, as these data, be they water demand values or electricity prices, cannot be modeled perfectly, the associated uncertainty is shifted to the decision making process.

The high uncertainty in the operation of drinking water networks, as a result of the volatility of future demands as well as energy prices (in a deregulated energy market) is likely to lead to a rather expensive operating mode with poor quality of service (the network may not always be able to provide the necessary amount of water to the consumers). In control engineering practice, this uncertainty is often addressed in a worst-case fashion (Sampathirao et al., 2014; Wang et al., 2015) — if not neglected at all

* Corresponding author.
E-mail addresses: pantelis.sopasakis@kuleuven.be (P. Sopasakis), sampathirao@control.tu-berlin.de (A.K. Sampathirao), alberto.bemporad@imtlucca.it (A. Bemporad), panos.patrinos@esat.kuleuven.be (P. Patrinos).
[1] The work of A. K. Sampathirao was supported by the German Federal Ministry for Economic Affairs and Energy (BMWi), Project No. 0324024A.
[2] The work of P. Patrinos was supported by the KU Leuven Research Council under BOF/STG-15-043.

https://doi.org/10.1016/j.envsoft.2017.11.035
1364-8152/

— leading to conservative and suboptimal control policies. It is evident that it is necessary to devise control methods which take into account the probabilistic nature of the underlying uncertainty making use of the wealth of available historical data aiming at a proactive and foresightful control scheme which leads to an improved closed-loop performance. These requirements necessitate the use of *stochastic model predictive control*: an advanced control methodology where at every time instant we determine a sequence of *control laws* which minimizes the *expected value* of a performance index taken with respect to the distribution of the uncertainty (Mesbah, 2016). Optimization-based approaches for the operational management of water networks have been studied and are well established in engineering practice (Mala-Jetmarova et al., 2017).

Indeed, scenario-based stochastic model predictive control (SSMPC) has been shown to lead to remarkable decrease in the operating cost and improvement in the quality of service of drinking water networks (Sampathirao et al., 2017a). In SSMPC, the uncertain disturbances are treated as random variables on a discrete sample space without assuming any parametric form for their distribution (Calafiore and Campi, 2006). The scenario approach was identified in a recent review as a powerful method for mitigating uncertainty in environmental modeling related to water management (Horne et al., 2016). Although this approach offers a realistic control solution as it is entirely data-driven, this comes with considerable computational burden as the resulting optimization problems are of particularly large scale (Goryashko and Nemirovski, 2014; Grosso et al., 2014a). This has rendered the use of SSMPC prohibitive and has hindered its applicability. Indeed, hitherto there have been used only conventional model predictive control approaches (Ocampo-Martinez et al., 2010; Bakker et al., 2013), robust worst-case formulations (Sampathirao et al., 2014; Ocampo-Martinez et al., 2009; Tran and Brdys, 2009) and stochastic formulations where the underlying uncertainty is assumed to be normally identically independently distributed (Wang et al., 2016a; Grosso et al., 2016). Note that it has been observed that demand prediction errors are typically follow heavy-tail distributions which cannot be well approximated by normal ones (Hutton and Kapelan, 2015).

In this paper, we present a software for the fast and efficient solution of such problems harnessing the immense computational capabilities of graphics processing units (GPU) building up on our previous work (Sampathirao et al., 2017a, 2016, 2015).

There has been recently a lot of interest in the development of efficient methods for stochastic optimal control problems such as stochastic gradient methods (Themelis et al., 2016a), the alternating directions method of multipliers (ADMM) (Kang et al., 2015) and various decomposition methods which can lead to parallelizable methods (Carpentier et al., 2010; Defourny et al., 2012) (the most popular being the stochastic dual approximate dynamic programming (Jiang et al., 2014), the progressive hedging approach (Carpentier et al., 2013) and dynamic programming (Bertsekas, 2000)). There have been proposed parallelizable interior point algorithms for two-stage stochastic optimal control problems such as (Klintberg and Gros, 2017; Lubin et al., 2011; Kang et al., 2014; Chiang et al., 2014) and an *ad hoc* interior point solver for multistage problems (Hübner et al., 2017). However, interior point algorithms involve complex steps and are not suitable for an implementation on GPUs which can make the most of the capabilities of the hardware. Additionally, interior point methods cannot accommodate complex non-quadratic terms in the cost function such as soft constraints (distance-to-set functions).

At large, not many software and libraries are available for stochastic optimal control; one of the very few one may find on the web is JSPD, a generic Java stochastic dynamic programming library. QUASAR is a commercial tool for scenario-based stochastic optimization. One of the most popular tools in the toolbox of the water networks engineer is PLIO (Cembrano et al., 2011), which implements MPC algorithms. This work covers the yawning gap between engineering practice and the latest developments in control and optimization theory for drinking water networks. These results can also be applied for the control of other infrastructure with similar structure such as power grids (Hans et al., 2015).

1.2. Contributions and novelty

Despite the fact that SSMPC problems typically involve millions of decision variables, the associated optimization problems possess a rich structure which can be exploited to devise parallelizable *ad hoc* methods to solve the problem more than an order of magnitude faster than commercial solvers running on CPU.

The architecture of our implementation comprises three independent modules: (i) the *network* module, (ii) the *energy prices and water demands forecaster* and (iii) the *control module*. The network module provides a dynamical system model which describes the flow of water across the network together with the storage limits of the tanks and the constraints on pumping capacities. The network module defines a *safety storage level* for each tank — a level which ensures the availability of water in case of high demand and the maintenance of a minimum required pressure. The forecasters produce a *scenario tree*, that is, a tree of likely future water demands and energy prices, upon which a contingency plan is made by minimizing a cost function which quantifies the operating cost and the quality of service. Such scenario trees are constructed from historical data of energy prices and water demands. The control module computes flow set-points, which are sent to the pumping stations and valves, by solving a scenario-based stochastic model predictive control problem over a finite prediction horizon.

The proposed stochastic model predictive controller leads to measurable benefits for the operation of the water network. It leads to a more economic operation compared to methods which do not take into consideration the stochastic nature of the energy prices and water demands. In this paper, we assess the performance of the controlled network using three key performance indicators: (i) the *economic index*, (ii) the *safety index*, which quantifies the extent of violation of the safety storage level requirement and (iii) the *computational complexity index* with which we assess the computational feasibility of the controller. Simulation results are provided using data from the water network of Barcelona and the energy market of Austria. The advantages of the adopted control methodology are combined with the computational power of GPUs, which enables us to solve problems of very large scale.

1.3. Software

Our implementation is available as an open-source and free software which can be readily tailored to the needs of different water networks modifying the parameters of its modules. The implementation is done entirely in `CUDA-C++` and it can be configured either programmatically or using configuration files. The adopted object-oriented programming model is amenable to extensions and users may specify their own predictive models, scenario trees, cost functions, dynamical models and constraints. Our results are accompanied by extensive benchmarks and the software is verified with unit tests.