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An optimised placement of the hard quality sensors for a robust monitoring of the chlorine concentration in drinking water distribution systems

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ABSTRACT

The problem of an optimised placement of the hard quality sensors in drinking water distribution systems under several water demand scenarios for a robust monitoring of the chlorine concentration is formulated in this paper. The optimality is understood as achieving a desired trade off between the sensors and their maintenance costs and the accuracy of estimation of the chlorine concentration. The contribution of this work is a comprehensive approach to optimised sensor placement by addressing a single, bi and multi-objective problem formulations including a comparison of the proposed methods in terms of the number of hard sensors placed and the performance of the monitoring system. During the design of optimised sensors placement algorithms, the interval observer, recently developed by the authors is applied as the soft sensors. Finally, for the purpose of validating the performance of the algorithms, they are applied to the model of a real drinking water distribution system.

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1. Introduction

A drinking water distribution system (DWDS) is rated as one of the Critical Infrastructure Systems that are essential for functioning of modern society and economy [1]. An operation of the DWDS aims at delivering to the users the required amount of water satisfying the quality requirements [2]. Achieving this goal is complicated, therefore, on-line suitable control and monitoring systems are needed. Moreover, two aspects must be taken into account during control and monitoring in the DWDS: quantity and quality of water [3]. They interact but the relationship is only one way, from the hydraulics to the water quality [4]. This was utilised in an integrated approach to control of water quantity and quality presented in [5]. In particular, two-level hierarchical control structure was proposed and investigated. Moreover, the details of designing the lower level controller in the mentioned hierarchical structure was shown in [6]. In turn, the main task of the monitoring system is to provide information on the state of the DWDS. Because, the two above mentioned issues must be considered, from the monitoring point of view, two cascaded systems can be distinguished: the water quantity and the water quality. The robust estimates of the water flow rates and hydraulic model parameters are produced by the quantity monitoring system [7]. Furthermore, these flows estimates are the input data to the water quality models, hence, to the water quality monitoring system [3]. It is worth to add that one of the important elements for designing a water quality monitoring system is the optimised placement of available hard quality sensors. This paper addressed this issue especially.

The water quality in the DWDS can be described by several factors. The most popular one is the disinfectant concentration. At present, the chlorine is commonly used as a disinfectant [3]. The water quality monitoring system exploits water quality measurements in order to gather knowledge on the state of water quality. In typical DWDSs the water quality measurements are made at network nodes and in tanks. Hence, these elements of the DWDS are called nodes or tanks with the hard sensors. The water quality may be measured in laboratories or by using on-line sensors. The bacteriology measurements (e.g. the number of coli bacteria) are the typical laboratory measurements in DWDSs. It is worth to add that modern sensors for on-line bacterial counts measuring will appear and they are tested in DWDSs [8]. However, currently they are not widespread and, therefore, primarily the free chlorine concentrations are measured on-line in DWDSs. Henceforth, this

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Principal symbols and abbreviations

DWDS drinking water distribution system
NSGA-II Non-dominated Sorting Genetic Algorithm II
$\pm$ mark of upper and lower bounds, respectively
$|(\cdot)|$ number of elements in a set $(\cdot)$
$\|\cdot\|$ Euclidean norm
$\leq$ mark of element-wise compare
$\delta_l(\upsilon_\gamma)$ value of the lth objective function at the γth Pareto solution
$\delta_{rv,l}$ relative value of the lth objective function and $l \in L$
$\boldsymbol{\varepsilon}_{c_{out}}(t)$ measurement error
$|\boldsymbol{\varepsilon}_{c_{out}}(t)|$ absolute value of measurement error
$\boldsymbol{\varepsilon}_{c_{out}}^{\max}$ bound of measurement error
η real, arbitrary, positive and constant parameter
Γ set of Pareto solutions
Ω_1 set of all nodes in a DWDS
Ω_2 set of all tanks in a DWDS
$\Omega_E \subset \Omega_1$ set of monitored nodes in a DWDS
υ_γ the γth Pareto solution and $\gamma \in \Gamma$
υ^* the best solution among Pareto solutions
$\boldsymbol{A}(t) \in \mathbb{R}^{n\times n}$ state matrix
ASR number of available sensors
$\boldsymbol{b}(t) \in \mathbb{R}^n$ vector of inputs
$c_{f,h}^+(k)$ upper envelope bounding unknown chlorine concentration in the hth tank
$c_{f,h}^-(k)$ lower envelope bounding unknown chlorine concentration in the hth tank
$c_{out,r}^+(k)$ upper envelope bounding unknown chlorine concentration at the rth node
$c_{out,r}^-(k)$ lower envelope bounding unknown chlorine concentration at the rth node
$c_{f,h,ob}^+(k)$ upper envelope bounding unknown chlorine concentration in the hth tank for the obth water demand scenario
$c_{f,h,ob}^-(k)$ lower envelope bounding unknown chlorine concentration in the hth tank for the obth water demand scenario
$c_{out,r,ob}^+(k)$ upper envelope bounding unknown chlorine concentration at the rth node for the obth water demand scenario
$c_{out,r,ob}^-(k)$ lower envelope bounding unknown chlorine concentration at the rth node for the obth water demand scenario
dis_{rv,υ_γ} relative distance of the γth Pareto solution from a coordinate system origin
d_t derivative with respect to t
$f_{p,(\cdot)}$ penalty function identified by $(\cdot)$
$g_{sfr} \in SFR$ decision variable allocating hard sensor to sensor feasible nodes
$h \in \Omega_2$ individual tank
$\boldsymbol{I}$ identity matrix
k discrete time instant and $k = 1, 2, \ldots, K$ and $K = \frac{T}{T_{QP}}$
L set of objective functions
m number of measured quality state variables
n number of quality state variables
$\boldsymbol{N}_1 \in \mathbb{R}^{s\times s}$ invertible matrix proportional to the identity matrix
ob individual water demand scenario
$P_{(\cdot)}$ positive, real number identified by $(\cdot)$
$P_{r,3}$ positive, real number for the rth node
$P_{h,4}$ positive, real number for the hth tank
$r \in \Omega_E$ individual monitored node
$\mathbb{R}$ set of real numbers
s number of unmeasured quality state variables
$\boldsymbol{S}^\pm$ interval observer
SC set of all considered water demand scenarios
$SFR \subset \Omega_1$ set of nodes where sensors can be located (sensor feasible nodes)
t time instant
T considered time horizon
T_{QP} quality sampling interval
$\boldsymbol{w}(t)$ auxiliary variable
$\boldsymbol{x}(t) \in \mathbb{R}^n$ vector of quality state variables
$\boldsymbol{x}_1(t) \in \mathbb{R}^s$ vector of unmeasured quality state variables
$\hat{\boldsymbol{x}}_1^\pm(t)$ upper and lower bounds on estimated state variables, respectively
$\boldsymbol{x}_2(t) \in \mathbb{R}^m$ vector of measured quality state variables
$\boldsymbol{x}_2^\pm(t)$ upper and lower bounds on measured state variables, respectively
$\tilde{\boldsymbol{x}}_2(t)$ vector of indirectly measured state variables (pseudo measurements)
$X_{1,max,r}$ upper limit on estimation accuracy at the rth node
$X_{2,max,h}$ upper limit on estimation accuracy in the hth tank
$\boldsymbol{y}_{c_{out}}(t)$ vector of measurements

concentration will be considered as the water quality factor in this work. Moreover, without any loss on generality it is assumed that the hard sensors of the chlorine concentration can be placed only at the DWDS nodes. Hence, in this paper the water quality state is meant as a set of the chlorine concentrations in crucial elements (e.g. tanks) of the DWDS.

Unfortunately, placing the chlorine concentration sensors at all DWDS nodes is not possible. It is due to e.g. high costs of hard sensors as well as their maintenance and the access limitations for their installation. Therefore, in this paper the estimates of unmeasured chlorine concentrations called soft sensors are used to complete the measurement information delivered by the hard sensors. Typically, the DWDS is composed of: pumps, valves, pipes, nodes, tanks and reservoirs. The pumps and the valves are used to control the hydraulic quantities that are the water flow rates and pressures. Hence, the DWDS water quality model takes into account changes of the chlorine concentration at the nodes, in the tanks and along the pipes. A problem of changes in water quality in the DWDS was noticed e.g. in [9]. Because the chlorine reacts with organic and non-organic matter in water, the chlorine concentration decreases with time [10]. During formulation of models of the chlorine concentration decay, it is commonly assumed that the hydraulic solution of the DWDS (the values of the water flow rates within the pipes etc.) is known and it is constant over a specified time interval called the hydraulic step. The models of chlorine decay during water transfer through the DWDS can be found in many publications. For instance modelling of changes of the chlorine concentration in tanks was presented in [11]. In turn, a general description modelling and simulation of water quality can be found in [12]. While a comparison between the formulation and computational performance of four numerical methods for modelling chlorine concentration dynamics was shown in [13]. In turn, a continuous lumped model of the chlorine concentration can be found in [3]. Moreover, it is necessary to derive a model of the uncertainty. One of the practical approach is the set-membership [7]. The set bounded estimation with the interval observer of the chlorine concentration recently developed by the authors was presented in [3]. By integrating both models and measurements, the estimation algorithm is obtained. It provides the estimates of unmeasured chlorine concentrations. It is neces-

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