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Controllability analysis as a pre-selection method for sensor placement in water distribution systems

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ABSTRACT

Detection of contamination events in water distribution systems is a crucial task for maintaining water security. Online monitoring is considered as the most cost-effective technology to protect against the impacts of contaminant intrusions. Optimization methods for sensor placement enable automated sensor layout design based on hydraulic and water quality simulation. However, this approach results in an excessive computational burden. In this paper we outline the application of controllability analysis as preprocessing method for sensor placement. Based on case studies we demonstrate that the method decreases the number of decision variables for subsequent optimization dramatically to app. 30 to 40 percent.

1. Introduction

Placement of sensors in water distribution systems (WDSs) fulfills various objectives regarding modeling and operational control of such networks, such as data collection for parameter calibration, standard water quality monitoring [see e.g. Aisopou et al. (2012)], detection of contaminant intrusion (see e.g. Arad et al., 2013), etc. This manuscript focuses on the last aspect and discusses some aspects regarding sensor placement in WDSs for contaminant detection.

Contamination warning systems (CWSs) are expected to be a cost-efficient technology to mitigate risks (ASCE2004; American Water Works Association (AWWA) 2005; Janke et al. 2006; U.S. EPA, 2005). Thus far, as it is too costly to place sensors at all locations in a network, a key issue in the design of CWS is the strategic placement of sensors within the distribution system (Storey et al., 2011). The placement strategy aims to minimize the potential public health impact from any contamination intrusion with a limited number of sensors (Hart and Murray, 2010). Note that usually at maximum a few tens of sensors are placed in a system. Thus far, three main approaches of sensor placement are described in the literature: empirical methods (Berry et al., 2005; Trachtman, 2006), empirically-based methods (Bahadur et al., 2003; Ghimire and Barkdoll, 2006; Xu et al., 2008), and optimization methods. Here, the empirically based methods refer to the ranking of potential sensor locations (Hart and Murray, 2010) based on expert information (e.g. data from geographical information

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system). Among these methods, optimization methods are the most advocated ones today, given their capability to enable automated sensor placement based on hydraulic and water quality simulation. Thus, a sensor network that minimizes contamination risks could be automatically planned using computationally search methods.

Ostfeld et al. (2008) compared 15 different approaches for sensor placement in the battle of the water sensor networks (BWSN). The current available optimizers are mainly based on integer programming (e.g. Lee and Deininger, 1992), mixed-integer programming (e.g. Propato, 2006), heuristic-based algorithms (e.g. Dorini et al., 2006), graph theory algorithms (e.g. Kessler et al., 1998), and genetic algorithm schemes (e.g. Ostfeld and Salomons 2004).

Although these methods can find near optimal sensor layouts (Hart and Murray, 2010), there are still obstacles and knowledge gaps, as pointed out by Hart and Murray (2010) based on results from real-world large utility networks. One of the most noteworthy obstacles is the computational efficiency. On the one hand, distribution networks are complex systems resulting in significant computational effort for water quality simulation (see also Arad et al., 2013). On the other hand, the optimization methods (especially GAs) entail a high computational cost in order to achieve a sound level of good solutions. Consequently, trade-offs between accuracy of the result and efficiency of the computation are commonly unavoidable. For instance, detailed models of the distribution network may be replaced by simplified ones (Perelman and Ostfeld, 2011). Further, with the exception of the TEVA-SPOT toolkit (Berry et al., 2008; Hart, 2008), existing sensor placement optimization methods assume that only a fixed number of sensors will be used in a CWS. To allow for a more efficient optimization - albeit less accurate result – the optimization strategies are frequently reformulated to reduce the solution sets [e.g. by decreasing the number of decision variables (Berry et al., 2007and Hart et al., 2008) and/or the number of considered scenarios (Preis and Ostfeld, 2007)].

Independent from the efforts to re-formulate the optimization methods, the prior use of preprocessing strategies is another generally applicable technique for reducing the computational load (Hart and Murray, 2010). For example, contamination simulations can be excluded from the optimization process by performing offline simulations as a preprocessing step (Berry et al., 2006; Chastain, 2006; Krause et al., 2008; Propato, 2006). As the most efficient way to speedup the process is the reduction of the number of candidate nodes, Guan et al. (2006) and Aral et al. (2008) introduced the sub-domain approach into the genetic algorithm. Specifically, a roulette wheel method was applied to choose the sub-domain based on nodal water demands for all scenarios. Huang et al. (2008) used a prior preparation of the database to provide initial solutions for optimization. The database stores data for intrusion events at each node and the classified consequences of these intrusions. By exploiting the submodularity property of objective functions, the approach proposed by Krause et al. (2008) can achieve at least a fraction of $(1 - 1/e)$ of the optimal solution, and therefore can handle real-world networks of size up to 21,000 nodes. Another pre-processing approach to reduce the computational effort in deriving the optimal sensor placement strategy is to develop methods that deepen insights into the structure and mechanism of distribution systems and subsequently allow for a pre-selection of optional sensor locations. Only a few studies have been done in this context. Deuerlein (2008) developed a generalized decomposition model that simplifies a network into a graph consisting of two main components, called forests and cores, respectively. The model is applied to the risk analysis and sensor placement for WDS security (Deuerlein et al., 2010). Perelman and Ostfeld (2011) developed topological clustering tools for WDS analysis. As clusters result from the flow directions in pipes, the placement of sensor can be proposed.

This study explores sensor placement for contaminant detection in WDS on the basis of insights gained from control theory-oriented complex system analysis. Specifically, this paper introduces a novel method for improving sensor placement based on controllability analysis as outlined by Liu et al. (2011). The key idea is to reduce the parameter set for sensor placement optimization by minimizing the number of possible locations. According to control theory, a dynamical system is controllable if driving a suitable set of nodes by different signals can offer full control over the network. The selected nodes are termed as “driver nodes”. Here, the term full control refers to driving the system from any initial state to any desired final state within finite time (Kalman, 1963; Luenberger, 1979; Slotine and Li, 1991). Thus, every node in the system should receive the corresponding signal from the driver node within finite time. Typically, controllability analysis is related to actuator placement. Nevertheless, the method for actuation can be extended to sensing through an inversion of the inputs and outputs [also refer to observability (Kalman, 1959; Campbell et al., 1991; Trease and Kota, 2006; Liu et al., 2013)]. The new system, driven from such an inversion, is termed as the dual or adjoint system (e.g. $A^{T}v = g$) of the original one (e.g. $Au = f$). The equivalence of the two forms is easily proved as $v^{T}f = v^{T}Au{=}(A^{T}v)^{T}u = g^{T}u$ (Giles and Pierce, 2000). If in the dual system, $\forall n_i \in N$ ($n_i$is a node, and $N = \{n_1,\dots, n_m\}$) a path from a certain driver node d_j to n_i always exist, the status of any node n_i can also be delivered to the corresponding driver node(s) d_j in the original system.

In the context of WDS analysis, the driver nodes in the dual system of the original WDS are likely to be proper places for sensor placement given the reason described above. Specifically, as in this case matrix A could be an adjacency matrix ($A_{ij} = -A_{ji} = a_{ij}$ if node i and j are connected, where a_{ij} is the weight of the directed link, $i \rightarrow j$; or $A_{ij} = A_{ji} = 0$ otherwise). The dual system is subsequently a water distribution network with reversed flow direction in every link (A^{T}). The dual system is subsequently a water distribution network with reversed flow direction in every link (A^{T}). Consequently, the input signals at driver nodes could be regarded as time-dependent indicator for contamination events (e.g. the contaminant’s concentration). Therefore, the signal (contamination intrusion) will definitely be detected at driver nodes. As the network is fully controlled by driver nodes, it might be possible to identify the contamination source(s) in finite time by tracing back along the directed paths from the driver nodes (where intrusion events are detected) to all linked upstream nodes. Thus, given the simplifying assumptions of the approach as e.g. that any pollutant does not vanish due to