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Sampling design for leak detection in water distribution networks

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Abstract

The leak detection, as well as other tasks related to control and management of water distribution systems (WDS), depends on representative data on the actual state of the system, ie, reliable values for state variables acquired by sensors. Given that the number of such sensors, as well as its location in the WDS, interferes with the usability of the acquired data, the careful design of the sampling points is necessary. Although many researchers have already addressed this issue, only some of them have focused on the specific purpose of leak detection, so that there is still no known efficient solution to this problem and improvements can be achieved by exploring different criteria and solving methods.

The aim of the study here described is develop a sampling design (SD) method for localization and quantification of pressure sensors in WDS, aiming leak detection. According to the proposed method, the search for the proper SD is driven by four criteria: maximization of total leak sensitivity and sensitivity consistence, and minimization of information redundancy and sensors number. The sensitivity analysis is developed using a hydraulic simulation model of the network and incorporating artificial node leaks as pressure-driven demands. Entropy is used to estimate the consistence of sensitivity to all the considered leak events. Redundancy is evaluated by the correlation between simulated responses, in terms of pressure at potential nodes for sensors installation. Finally, reducing the number of sensors is targeted, admitting that generally their availability is limited. The optimization procedure uses the multiobjective genetic algorithm NSGAII approach to search for the complete set of nodes for sensors placement.

In addition to the method explanation, its application for an existing water supply district is presented, producing a consistent near-optimal set of nine well distributed places for sensor installation. The SD method proposed here could be applied to any WDS and assist advances for data-driven detection of leaks, and even for intelligent systems development for WDS.

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Keywords: Sampling design; leak detection; pressure sensors; sensor placement; water supply systems.

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1. Introduction

Recently, researchers and technicians concerned about water distribution systems (WDS) have focused their efforts on deal with control and management issues, commonly having as input the knowledge of the actual system state. Therefore, the constant and accurate monitoring of state variables like pressure or flow is essential, but can be made only using sensors in strategic points of the network. The confidence and usability of such discrete data to infer the whole system state depends on the number and placement of points where sensors are installed [1]. Thus the decisions about sampling design (SD) should be well substantiate.

The meaning of a "good" SD is different for each application, as the data analysis is very different from direct detection of contamination intrusion to calibration of complex hydraulic models or intelligent data analysis for leak detection. On balance, there is not a completely established solution for several purposes, such as leak detection, calibration, contamination intrusion, etc., and since techniques based in acquired data have been increasingly researched [2], the development of specific SD methods aiming leak detection is an important task.

Regard the researches related to sampling in WDS reported in literature, some of them are focused on contamination detection [3,4], with the main objective of fast sensing of deliberate or accidental hazardous substance intrusion. Proposals include several approaches, most of them using hydraulic/quality models and different optimization methods. The main differences between contamination and leak detection problems are related to the analysis of sensors data to infer whether the WDS state is normal or altered, seeing that this task is much more indirect and complex in the leak detection situation. SD have been studied also for model calibration purposes, commonly evaluating the sensitivity of the state variables - pressure or flow - due to changes in the variables to be calibrated, for instance, pipes roughness [5–7].

The sensitivity definition is the first limitation to directly apply those methods for the leak detection problem. Focusing on publications about SD for leak detection purpose, the pressure sensitivity is analyzed considering changes in the WDS due to eventual leaks. The sensitivity idea have been used as objective of sensor location comparing only the nodal pressure values for leak and no-leak conditions [8], and considering also the output flow variation to obtain a relative pressure variation [9]. The last one is closer to the classical definition [1], also used by the authors referred in the following paragraphs: sensitivity is the partial derivate of the measured parameter (pressure) in relation with the changing parameter (flow). The locations selection proposed in [8] is directly based on the sensitivity value of each node, selecting the more sensitive ones to compose the solution set. This approach has as deficiency the possible selection of neighbor nodes or of nodes highly sensitive to some simulated leaks but non-sensitive to the most.

Clustering analysis is proposed in [10], using a self-organizing map (SOM) in order to classify the network nodes according their similarity in terms of pressure sensitivity to leaks. The method determines the amount of clusters and their composition in order to reach a sensitive-based threshold value, and then the nodes obtained as clusters center are chosen for sensor placement. As reported, not only the threshold value but parameters of the SOM affect the amount and location of chosen nodes, and the judgment of well-distributed places is limited to visual observation of hydraulic model scheme, being these considerable limitations.

In other contribution to the field [11] the sensitivity matrix is projected with the pressure changes in sensor-candidate nodes because a leak (different of the leak considered in the sensitivity matrix evaluation). Then, the projection for each candidate set, analized for all possible leak location, becomes the basis of decision criteria. Additionally, it is proposed to add a distorcion to sensitivity matrix in order to consider the uncertainties. Finally, the near-optimal solution is obtained using differential evolution, a special genetic algorithm (GA). Even applying a different sensitivity analysis, no other criterion is considered in the optimization.

The SD problem is in fact a multi-objective problem [3], but, as far as we know, the existing proposals for application in leak detection do not include this feature. The overcome of the mentioned limitations can improve the applicability of the SD procedures and encourage advances in intelligent leak detection methods.

The purpose of this paper is present a SD method which defines the best number of pressure sensors and set of nodes for placing them, for a given supply district represented by a hydraulic simulation model. The proposed method includes the analysis of four criteria: high total leak sensitivity, high sensitivity consistence, low information redundancy and reduced number of sensors. The first three objectives are evaluated simultaneously in the sensor location optimization process, using a multiobjective GA methodology, and the last one is used for sensor number

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