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Sensor Placement for Leak Location in Water Distribution Networks using the Leak Signature Space

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Abstract: In this paper, a sensor placement approach to improve the leak location in water distribution networks is proposed. The sensor placement problem is formulated as an integer optimization problem where the criterion to minimize is the number of overlapping signature domains computed from the leak signature space (LSS) representation. A stochastic optimization process is proposed to solve this problem, based on either a Genetic Algorithms (GA) or a Particle Swarm Optimization (PSO) approach. Experiments on two different DMAs are used to evaluate the performance of the resolution methods as well as the efficiency achieved in the leak location when using the sensor placement results.

Keywords: Water distribution networks, Leak isolation, Sensor placement, Leak signature space.

1. INTRODUCTION

Currently, in a world struggling to satisfy the water demands of a growing population, leaks are estimated to account up to 30% of the total amount of extracted water. To face these challenges, encouraging new technologies arose during the last decades (Colombo et al., 2009), achieving higher levels of efficiency and that came together with novel methods for leakage management.

Despite these first results, the performance obtained until now is still far from allowing the detection of leaks in Water Distribution Networks (WDN) with only a few sensors in a robust and fast way. A major limitation is that the performance achieved is highly dependent on the location of the sensors installed in the network. The development of a sensor placement strategy has been an extensive subject of research. In the context of water systems, some work has been done regarding sensor placement for leak location. Sarrate et al. (2012), defines an isolability index and use it to place the sensors in order to maximize the number of isolable node pairs. Closer to this work, Pérez et al. (2011) used thresholds on the differences of pressures measured to obtain binary matrices that were used to translate the sensor placement problem to an integer programming optimization problem. In Casillas et al. (2013), a new approach for sensor placement for leak location in WDN is proposed that is based on the projection-based location scheme proposed in Casillas et al. (2012, 2014a). Actually, leak location and sensor placement should be considered together since the best placement depends on the method that is used to locate the potential leaks and the efficiency of the leak location depends on the sensor placement.

This paper introduces a model-based optimization method for near-optimal sensor placement to detect leak nodes in WDN. It relies on the so-called Leak Signature Space (LSS), an original representation where a specific signature is associated to each leak location that minimizes the dependence with its magnitude (Casillas et al., 2014b). The proposed approach allows to place adequately the sensors in a WDN in order to take the best benefit of the LSS based leak detection method.

The paper is organized as follows. In Section 2, the LSS method that is used for the leak location is introduced. Section 3 formulates the sensor placement optimization problem while Section 4 shows the methods proposed to solve it. Section 5 evaluates the performance of the approach on a real WDN through several scenarios. Finally, Section 6 summarizes the contribution and indicates points that deserve further attention.

2. LSS BASED LEAK LOCATION METHOD

This section presents the LSS method proposed in Casillas et al. (2014b) that is used to locate the leaks. It is based on the linear approximation of the dependency between the leak magnitude and the pressure residuals. Such model, is used to perform a transformation that allows to represent node leaks by means of points in the LSS, independently of the leak magnitude. Thus, by means of the LSS method the potential leak node can be characterized by a given signature.

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2.1 Leak magnitudes linear dependency approximation

Here, let us assume that the behavior of the WDN follows the models described by Todini and Pilati (1988), and that it consists of m nodes, f pipe flows and n pressure sensors located at the nodes (typically $n \ll m$). Let us also define the vectors $\mathbf{p}$, $\mathbf{p}^*$, $\mathbf{q}$, $\mathbf{d}$ which are respectively the vectors of pressure in the junction nodes, pressure in reservoirs, flows trough the pipes and demands:

$$\begin{aligned} \mathbf{p} &= (p_1, \cdots, p_m)^{\mathbf{T}}, \\ \mathbf{p}^* &= (p_1^*, \cdots, p_u^*)^{\mathbf{T}}, \\ \mathbf{q} &= (q_1, \cdots, q_f)^{\mathbf{T}}, \\ \mathbf{d} &= (d_1, \cdots, d_m)^{\mathbf{T}}, \end{aligned} \quad (1)$$

with u corresponding to the number of reservoirs supplying the WDN. According to the representation proposed in Todini and Pilati (1988), the water network model can be solved numerically, using a Newton-Raphson iterative scheme, where the iteration $k+1$ is given by the following set of equations:

$$\begin{aligned} \mathbf{q}^{k+1} &= (I - N^{-1})\mathbf{q}^k - N^{-1}A_{11}^{-1}(\mathbf{q}^k)(A_{12}\mathbf{p}^k + A_{10}\mathbf{p}^*), \\ \mathbf{p}^{k+1} &= -(A_{21}N^{-1}A_{11}^{-1}(\mathbf{q}^k)A_{12})^{-1} \cdot \\ &\quad \left(A_{21}N^{-1}(\mathbf{q}^k + A_{11}^{-1}(\mathbf{q}^k)A_{10}\mathbf{p}^*) + (\mathbf{d} - A_{21}\mathbf{q}^k)\right), \end{aligned} \quad (2)$$

where N is a diagonal matrix such that $N = \text{diag}(\gamma_i)$, $i \in [1, \cdots, f]$, $A_{12} = A_{21}^T$, $A_{10} = A_{01}^T$ with A_{21}, A_{01} being incidence matrices, $A_{11}(\mathbf{q}) = \text{diag}(c_i|q_i|^{\gamma_i})$, $|q_i|$ is the absolute value of the flow q_i, c_i is a constant parameter which depends on the diameter, the roughness and the length of the pipe, and γ_f is the flow exponent parameter. It is important to note that this resolution approach is commonly employed, as e.g. in the EPANET simulator (Rossman, 2000) where large WDN can be simulated efficiently.

The solution of the system of equations (2) corresponds to the case where an equilibrium point has been reached for the network, i.e. the flows and pressures are constant along the time which means $\mathbf{p}^{k+1} = \mathbf{p}^{\mathbf{k}} = \mathbf{p}$ and $\mathbf{q}^{k+1} = \mathbf{q}^{\mathbf{k}} = \mathbf{q}$. A thorough representation of a WDN would theoretically involve a graph structure where each possible leak is assumed to be located in a graph node. However, a leak could possibly appear at any point of any network pipe. For this reason, the exact modeling of any possible leak becomes unfeasible in practice. To mitigate this issue, it is usually assumed that leaks only appear in the network nodes (see, e.g. Pudar and Liggett (1992) among others). With such assumption, the leak can be written as a vector of extra demands $\mathbf{\Delta d}$ and the new demand $\mathbf{d}'$ can be expressed such as:

$$\mathbf{d}' = \mathbf{d} + \mathbf{\Delta d}, \quad (3)$$

where $\mathbf{\Delta d}$ is a m dimensional vector with zeros everywhere except at the node's index where the leak occurs. Now, assuming that the network flow equilibrium has also been reached in presence of leak, the new pressure can be expressed as:

$$\begin{aligned} \mathbf{p}' &= -(A_{21}N^{-1}A_{11}^{-1}(\mathbf{q}')A_{12})^{-1} \cdot \\ &\quad \left(A_{21}N^{-1}(\mathbf{q}' + A_{11}^{-1}(\mathbf{q}')A_{10}\mathbf{p}^*) + (\mathbf{d} + \mathbf{\Delta d} - A_{21}\mathbf{q}')\right) \end{aligned} \quad (4)$$

Then, we propose to represent the residual $\mathbf{r}$ (c.f. Pérez et al. (2011)) as the difference between the nominal pressure obtained using the model without leaks and the pressure determined using the model in case of a leak. Assuming that the flow is approximately the same with and without leak ($\mathbf{q} \cong \mathbf{q}'$), we have:

$$\mathbf{r} = \mathbf{p} - \mathbf{p}', = (A_{21}N^{-1}A_{11}^{-1}(\mathbf{q})A_{12})^{-1}\mathbf{\Delta d}, = \mathbf{S} \cdot \mathbf{\Delta d}. \quad (5)$$

As one can see, it is possible to use a linear approximation of the relation between the residual (and consequently with the pressure measurement) and the leak through a $\mathbf{S}$ matrix factor, under equilibrium assumptions, that is known as the *sensitivity matrix*. However, in presence of a leak, a change will occur in the flow due to the extra demand occurring in one node of the network. Fortunately, the flow changes will be small for the problem addressed by our leak location method. In our case, we focus on medium size leaks, i.e., leaks ranging from 2 to 6 lps, which corresponds to medium ranges in leaks that occurs in the studied networks. Such range is chosen since smaller leaks are masked by uncertainties in the network and larger leaks usually reach the surface rapidly. This approximation involves to include an error factor $\varepsilon_{\mathbf{q}}$ that deviates from this linear approximation relation as $\mathbf{r} = \mathbf{S} \cdot \mathbf{\Delta d} + \varepsilon_{\mathbf{q}}$. This error is not modeled in the theoretical approximation but it will be taken into account in the realistic cases analysed in the experiments. The $\mathbf{S}$ matrix has been used in a variety of works (Pérez et al., 2011; Casillas et al., 2014a, 2012).

The pressure in a network at a given time instant can be represented by a point in the m-dimensional space of the pressure measurements. In case of a leak, equation (5) indicates that the position of this point is located on a line passing through the origin and whose direction depends on the node where the leak occurs. Moreover, the position of the point on the line depends on the leak magnitude. However, in practice, pressure measurements are accessible in only a limited number of nodes n, that correspond to locations where the sensors are placed. Fortunately, the n-dimensional space of the sensors is a subspace (a projection) of the m-dimensional space of the pressure measurements. Thus, this linear dependency is also valid in this projected space.

2.2 Leak signature space

The linear dependency presented above is such that for any pair of residual vectors $\mathbf{r}_1$ and $\mathbf{r}_2$ corresponding to different leak magnitudes but occurring in the same node j, it can be stated that:

$$\mathbf{r}_2^j = \alpha \mathbf{r}_1^j, \quad (6)$$

with α proportional to the leak magnitude. Thus, any residual corresponds to a direction vector of the line representing the leak at a specific node. Based on the sensor representation, it is possible to use the projection of the direction vector onto a selected hyperplane of the n-dimensional space. For simplicity, let us assume for now that the last coordinate is chosen to form the hyperplane, such that for a given residual $\mathbf{r}^j = [r_1^j, \cdots, r_n^j]^{\mathbf{T}}$ the projection vector $\bar{\mathbf{r}}^j$ is computed as:

$$\bar{\mathbf{r}}^j = [\frac{r_1^j}{r_n^j}, \cdots, \frac{r_{n-1}^j}{r_n^j}, 1]^{\mathbf{T}}. \quad (7)$$

Thus, there is a unique expression of such projection vector for a linear representation of the residuals. Consequently,