Journal of Process Control 55 (2017) 1–9

Contents lists available at ScienceDirect

Journal of Process Control

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

Leak localization in water distribution networks using Bayesian classifiers

Adrià Soldevila[a,*], Rosa M. Fernandez-Canti[a], Joaquim Blesa[b], Sebastian Tornil-Sin[a,b], Vicenç Puig[a,b]

[a] Research Center for Supervision, Safety and Automatic Control (CS2AC), Rambla Sant Nebridi, s/n, 08022 Terrassa, Spain
[b] Institut de Robòtica i Informàtica Industrial (CSIC-UPC), Carrer Llorens Artigas, 4-6, 08028 Barcelona, Spain

ARTICLE INFO

Article history:
Received 5 August 2016
Received in revised form 24 March 2017
Accepted 28 March 2017

Keywords:
Fault diagnosis
Bayesian classifier
Water distribution networks
Leak localization

ABSTRACT

This paper presents a method for leak localization in water distribution networks (WDNs) based on Bayesian classifiers. Probability density functions for pressure residuals are calibrated off-line for all the possible leak scenarios by using a hydraulic simulator, and considering the leak size uncertainty, demand uncertainty and sensor noise. A Bayesian classifier is applied on-line to the computed residuals to determine the location of leaks in the WDN. A time horizon based reasoning combined with the Bayesian classifier is also proposed to improve the localization accuracy. Two case studies based on the Hanoi and the Nova Icària networks are used to illustrate the performance of the proposed approach. Simulation results are presented for the Hanoi case study, whereas results for a real leak scenario are shown for the Nova Icària case study.

1. Introduction

Water leaks are present to some extent in all water distribution networks (WDNs). They may imply important economic costs because of the amount of water loss, and the location and reparation efforts involved. In many WDNs, losses due to leaks are estimated to account up to 30% of the total amount of extracted water [1]. This is a very significant amount since water is a precious resource in many parts of world that try to satisfy water demands of a growing population.

Several works have been published dealing with leak detection and isolation (localization) methods for WDNs (see [2] and references therein). For example, in [3], a review of transient-based leak detection methods is offered as a summary of current and past work. In [4], a method is proposed to identify leaks using blind spots based on previously leak detection that uses the analysis of acoustic and vibration signals [5], and models of buried pipelines to predict wave velocities [6]. More recently, Mashford et al. [7] have developed a method to locate leaks using support vector machines (SVM) that analyzes data obtained by a set of pressure control sensors of a pipeline network to locate and calculate the size of the leak. The use of *k*-NN and neuro-fuzzy classifiers in leak localization has been recently proposed in [8,9]. Another set of methods is based on the inverse transient analysis [10,11]. The main idea of this methodology is to analyze the pressure data collected during the occurrence of transitory events by means of the minimization of the difference between the observed and the calculated parameters. In [12,13], it is shown that unsteady-state tests can be used for pipe diagnosis and leak detection. The transient-test based methodologies use the equations for transient flow in pressurized pipes in frequency domain and then information about pressure waves is taken into account too.

Model-based leak detection and isolation techniques using stationary models have also been studied, starting with the seminal paper of Pudar and Liggett [14] which formulates the leak detection and localization problem as a least-squares parameter estimation problem. However, the parameter estimation of water network models is not an easy task [15]. The difficulty relies on the non-linear nature of water network model and the few measurements usually available with respect to the large number of parameters to be estimated that leads to an underdetermined problem. Alternatively, in [16,17], a model-based method that relies on pressure measurements and leak sensitivity analysis is proposed. In this methodology, pressure residuals, i.e. differences between pressure measurements provided by sensors and the associated estimations obtained by using the hydraulic network model, are computed on-line and compared against associated thresholds that take into account the effects of the modeling uncertainty and the noise.

* Corresponding author.
E-mail address: adria.soldevila@upc.edu (A. Soldevila).

http://dx.doi.org/10.1016/j.jprocont.2017.03.015
0959-1524/

When some of the residuals exceed their thresholds, the residuals are matched against the leak sensitivity matrix in order to discover which of the possible leaks is present. Although this approach has good efficiency under ideal conditions, its performance decreases due to the nodal demand uncertainty and noise in the measurements. This methodology has been improved in [18] where an analysis along a time horizon is taken into account and a comparison of several leak isolation methods is presented. It must be noticed that in cases where the flow measurements are available, leaks can be detected more easily since it is possible to establish simple mass balance relations in the pipes. See for example the work of [19] where a methodology to isolate leaks is proposed using fuzzy analysis of the residuals. This method finds the residuals between the flow measurements and their estimation using a model without leaks. However, although the use of flow measurements is feasible in large water transport networks, this is not the case in water distribution networks where there is a dense mesh of pipes with only flow measurements at the entrance of each district metering area (DMA). In this situation, water companies consider as a feasible approach the possibility of installing only a few pressure sensors inside the DMAs due to budget constraints [20], because they are cheaper and easier to install and maintain.

In this paper, a new method for leak localization in WDNs that uses Bayesian classifiers is proposed. The use of Bayes theory has already been proposed in the context of leak localization but not using Bayesian classifiers as proposed in this paper (see [21,22]). Bayes theory has also been proposed as a tool for diagnosis in [23,24]. Here, probability density functions of pressure residuals are calibrated off-line for all the possible leak scenarios using a hydraulic simulator where leak size uncertainty, demand uncertainty and sensor noise are considered. A Bayesian classifier is applied on-line to the available residuals to determine the location of leaks present in the WDN. A time horizon method combined with the Bayesian classifier is also proposed to improve the accuracy of the leak localization method. Two case studies based on the Hanoi and the Nova Icària networks are used to illustrate the performance of the proposed approach. Simulation results are presented for the Hanoi case study, whereas results for a real leak scenario are shown for the Nova Icària case study.

The remainder of the paper is organized as follows. Section 2 presents an overview of the overall leak localization methodology. Section 3 presents the details of the proposed Bayesian classifier approach. Section 4 shows the application of the method to the two considered WDNs. Finally, Section 5 draws the main conclusions of the work.

2. Methodology overview

The detection and localization of leaks in WDNs is a particular case of the problem of fault detection and isolation (FDI) in dynamic systems. The classical model-based FDI approach considers that this problem can be (on-line) solved by generating and evaluating residuals, i.e. differences between values computed through a system model and values provided by sensors that are indicative of faults.

Following the approach proposed in previous works [16,17], this paper proposes a method for leak localization based on the generation and analysis of pressure residuals. In contrast to these cited works, the analysis of the residuals is not limited to a Boolean or directional analysis and the use of a Bayesian classifier is proposed instead, being this the main contribution of the paper.

It is assumed that a small number of pressure sensors is installed in inner nodes of the network and that a hydraulic model has been built and tuned. On the other hand, it is considered that leaks only appear in the nodes of the network. Although this is not true in practice (leaks can also appear in pipes), the approximation is valid and useful for large and dense networks.

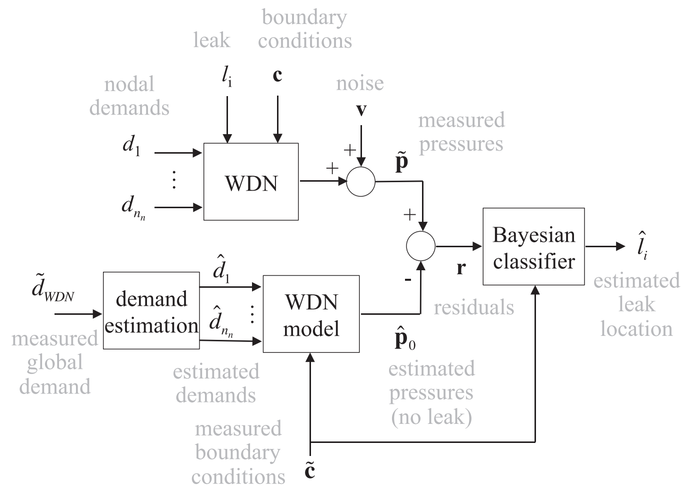

Fig. 1. Leak localization scheme.

Finally, it must be highlighted that the proposed method only addresses the leak localization problem, not the leak detection one, which is assumed to be solved by using any of the available techniques (for instance, leak detection can be based on detecting changes in the night consumption, which is the standard procedure used by most of water utilities [1] to monitor DMAs). Thus, the application of the proposed methodology assumes the existence of a leak detection module that triggers the operation of the leak localization module.

2.1. Basic architecture and operation

The method for on-line leak localization proposed in this paper relies on the scheme depicted in Fig. 1, based on computing pressure residuals and analyzing them by a Bayesian classifier.

Residuals ($\mathbf{r}$) are computed as differences between measurements provided by pressure sensors installed inside the DMA ($\tilde{\mathbf{p}}$) and estimations provided by a hydraulic model simulated under leak-free conditions ($\hat{\mathbf{p}}_0$). The hydraulic model is built using the Epanet hydraulic simulator [25] by considering the DMA structure (pipes, nodes and valves) and network parameters (pipe coefficients). It is assumed that, after the corresponding calibration process using real data, the model represents with accuracy the WDN behavior. However, it must be noticed that the model is fed with estimated water demands (typically obtained by the total measured DMA demand $\tilde{d}_{\mathrm{WDN}}$ and distributed at nodal level according to historical consumption records) in the nodes ($\hat{d}_1, \ldots, \hat{d}_N$) since in practice nodal demands ($d_1, \ldots, d_N$) are not measured (except for some particular consumers where automatic metering readers (AMRs) are available). Hence, the residuals are not only sensitive to faults but also to differences between the real demands and their estimated values. Additionally, pressure measurements are subject to the effect of sensor noise ($\mathbf{v}$) and this also affects the residuals. Taking all of these effects into account, the Bayesian classifier must be able to locate the real leak present in the WDN, that can be in any node and with any (unknown) magnitude, while being robust to the demand uncertainty and the measurement noise. Finally, it must be noted that the operation of the network is constrained by some boundary conditions ($\mathbf{c}$; for instance the position of internal valves and reservoir pressures and flows) that are measured ($\tilde{\mathbf{c}}$). These boundary conditions are taken into account in the simulation and can also be used as inputs for the classifier.