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HYDRAULIC STATE ESTIMATION: PILOT IMPLEMENTATION IN A WATER DISTRIBUTION SYSTEM

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Abstract

Hydraulic State Estimation (HSE) is an effective tool for water supply systems monitoring. This technique provides the most likely hydraulic state of the network by making use of the available measurements through the system and the associated hydraulic model, enabling to track uncertainty through the process. HSE has been applied to water transport networks before, but extending its application to distribution systems currently constitutes a challenge. The deployment of smart meters offers a unique opportunity to gain distributed information within the distribution level, but it also poses questions regarding the temporal resolution that is available/achievable and how to combine different sources of information. This work presents a real HSE implementation in a Spanish water distribution pilot area (approximately 1,000 inhabitants). Implementation is possible thanks to the systematic measurement of water consumption at each dwelling (with 1 minute and 1 L resolution) and flow and pressure at the inlet to the pilot area. This application is conceived to provide a better understanding of the challenges and opportunities for HSE implementation in water distribution systems.

Keywords
Water supply systems, distribution systems, smart meters, water consumption, household, high resolution.

1 INTRODUCTION

Water supply systems are currently being modernized thanks to the installation of metering devices and telemetry systems. These configurations are providing water utilities with large amounts of data, which must be processed to convert isolated readings into real information about how the system works. Hydraulic State Estimation (HSE) is an effective tool to process this data. It is posed as an optimization problem that provides the most likely hydraulic state by minimizing the difference between uncertain measurements (i.e. pressure measurements, flow measurements, demand measurements or estimations) and network variables (i.e. pressures and flows) while considering the hydraulic model equations as constraints [1]. This approach is more flexible than traditional hydraulic modelling and better suited for monitoring because it enables to consider any combination of measurements and their associated uncertainty to determine the flow regime [2].

HSE implementation requires that the network is observable, i.e. the number of measurements must be equal or greater than the number variables to be determined (i.e. unknowns) [3, 4]. However, this condition is not enough to ensure a successful state estimation. Since measurements are uncertain, uncertainty assessment is essential to quantify the quality of results [5, 6]. The interest and usefulness of HSE increases with the number of measurements, because it is when there are redundant measurements (i.e. more measurements than unknowns state variables) that state estimation really helps to identify the most likely state of the system based on all the available noisy inputs.

Measurement availability is therefore crucial to make the most of state estimation implementation. Since water systems have traditionally lacked metering devices, HSE deployment in this field has been slow. State estimation has been discussed in water supply systems on a scientific level for decades (see [7] for references), but its operational implementation is relatively scarce [8, 9, 10, 11]. The few applications that exist in the water domain focus in water transport networks [12, 13, 14]. Transport networks constitute the main arteries that convey water to District Metered Areas (DMA). DMA inflows are usually metered, which guarantees that a minimum number of measurements is available to run state estimation. The situation within DMAs or unstructured water distribution networks is different, because instrumentation is not so frequently available in distribution pipelines. The smart revolution is promoting the installation of meters at water service connections (i.e. at the entrance to each household, public building, industry, etc), offering a unique opportunity to gain distributed information throughout the system. However, the resolution of the new volume meters that may be located at water connections (which may provide 1 hour resolution as opposed to the traditional monthly volume read [15]) is usually poorer than the resolution of the flow meters located at the entrance to the DMA or other points within the transport/distribution network (1-15 minutes, e.g. [16]). These resolutions may also differ from the time resolutions usually adopted for monitoring or modelling purposes (15-60 minutes [17]). The impact of temporal resolution [18] and the need to level different temporal resolutions to implement HSE [19] has already been explored from a theoretical point of view in some archetypical examples, but according to the authors' knowledge it has never been explored in a real system.

The aim of this work is to present how a real HSE implementation is being put together in a pilot area (approximately 1,000 inhabitants) within a Spanish water distribution system. Apart from presenting the formulation required to implement HSE (and computing HSE uncertainty), the main characteristics of the measurement scheme (every minute 1 L resolution) are here presented. It is important to highlight that previous works have reached higher temporal resolutions in the past for specific demand characterization/disaggregation research purposes (up until the order of seconds, see [20] for references), but the emphasis of this work is to address the multi-scale problem rather than to focus on consumption particularities within the household. Therefore, this implementation will contribute to bridge the gap between the macro (network level) and the micro (household level) scales that coexist in water distribution systems.

2 METHODOLOGY

2.1 Hydraulic State Estimation

HSE minimizes the difference between available measurements or pseudomeasurements (i.e. estimations based on historical data [21]) and the equivalent network hydraulic variables, which are connected to each other through the hydraulic model equations (energy and continuity) and the so called state variables (set of independent variables that describe the network hydraulic state). The vector of differences between measured variables and corresponding measurements $\boldsymbol{\varepsilon} \in \mathbb{R}^m$ to be minimized can be generally defined as:

$$\boldsymbol{\varepsilon} = \boldsymbol{z} - \boldsymbol{h}(\boldsymbol{x}) \tag{1}$$

where $\boldsymbol{z} \in \mathbb{R}^m$ is the measurement vector, $\boldsymbol{x} \in \mathbb{R}^n$ is the state variable vector and $\boldsymbol{h}(\boldsymbol{x}): \mathbb{R}^n \rightarrow \mathbb{R}^m$ represents the function of non-linear relationships between the state and measured variables. Different criteria might be adopted to minimize the error as defined in Eq (1). According to the Weighted Least Squares (WLS) criterion, which is one of the most popular criteria for HSE [7], the problem can be posed as:

$$\min_{x} G(\boldsymbol{x}) = \frac{1}{2}\boldsymbol{\varepsilon}^{T}\boldsymbol{C_z^{-1}}\boldsymbol{\varepsilon} \quad (2)$$

$$\text{Subject to } \boldsymbol{f}(\boldsymbol{x}) = \boldsymbol{0} \quad (3)$$

Where $J(\boldsymbol{x})$ is the objective function that is to be minimized, $\boldsymbol{C_z} \epsilon \mathbb{R}^{m\times m}$ is the variance-covariance matrix of measurements and $\boldsymbol{f}(\boldsymbol{x})\colon \mathbb{R}^{n} \to \mathbb{R}^{c}$ is the function of equality constraints (e.g. transit nodes with null demand). Note that Problem (2)-(3) minimizes the errors between measurements and estimations, providing the most likely state of the system. This implies that, thanks to redundancy, the algorithm can probabilistically estimate the state of the system considering as more reliable those measurements that are consistent among each other and with the hydraulic model (see Figure 1). Inconsistent measurements may be detected as outliers, which are potentially useful to identify abnormal behaviours [14].

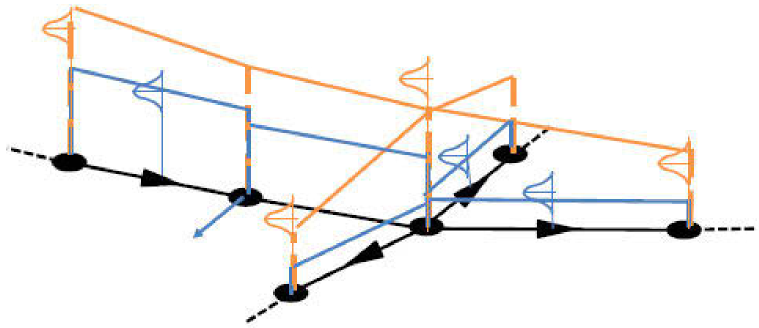

Figure 1. State estimation conceptualization in water supply systems

Problem (2)-(3) can be solved as a Newton iterative process:

$$\boldsymbol{x}_{i+1} = \boldsymbol{x}_i + \Delta\boldsymbol{x}_{i+1} \quad (4)$$

$$\begin{bmatrix} \boldsymbol{H}_i^T\boldsymbol{C}_z^{-1}\boldsymbol{H}_i & \boldsymbol{F}_i^T \\ \boldsymbol{F}_i & \boldsymbol{0} \end{bmatrix} \begin{bmatrix} \Delta\boldsymbol{x}_{i+1} \\ \boldsymbol{\lambda}_{i+1} \end{bmatrix} = \begin{bmatrix} \boldsymbol{H}_i^T\boldsymbol{C}_z^{-1}[\boldsymbol{z} - \boldsymbol{h}(\boldsymbol{x}_i)] \\ -\boldsymbol{f}(\boldsymbol{x}_i) \end{bmatrix} \quad (5)$$

Where i is an iteration counter, $\Delta\boldsymbol{x} \in \mathbb{R}^{n}$ is the vector of increments for the state variables, $\boldsymbol{H} \in \mathbb{R}^{m\times n}$ and $\boldsymbol{F} \in \mathbb{R}^{c\times n}$ are the Jacobian matrices of $\boldsymbol{h}(\boldsymbol{x})$ and $\boldsymbol{f}(\boldsymbol{x})$ respectively, $\boldsymbol{\lambda} \in \mathbb{R}^{c}$ represents the vector of dual variables and $\hat{\boldsymbol{x}}$ is the optimal solution to the problem. These equations have been particularised for different sets of state variables at water supply systems in [2].

2.2 Uncertainty quantification

HSE results are associated with uncertainty because the process nourishes from uncertain measurements/pseudomeasurements (matrix $\boldsymbol{C_z}$). The variance-covariance matrix for the state variables $\boldsymbol{C_x} \epsilon \mathbb{R}^{n\times n}$ can be computed once $\hat{\boldsymbol{x}}$ is known by applying the First-Order Second-Moment (FOSM) method [6]:

$$\boldsymbol{C_x} = \frac{\partial \boldsymbol{x}}{\partial \boldsymbol{z}}\boldsymbol{C_z}\left(\frac{\partial \boldsymbol{x}}{\partial \boldsymbol{z}}\right)^{T} \quad (6)$$

Where the sensitivity of the state and dual variables can be obtained as:

$$\begin{bmatrix} \frac{\partial \boldsymbol{x}}{\partial \boldsymbol{z}} \\ \frac{\partial \boldsymbol{\lambda}}{\partial \boldsymbol{z}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{H}^T\boldsymbol{C}_z^{-1}\boldsymbol{H} & \boldsymbol{F}^T \\ \boldsymbol{F} & \boldsymbol{0} \end{bmatrix}^{-1} \begin{bmatrix} \boldsymbol{H}^T\boldsymbol{C}_z^{-1} \\ \boldsymbol{0} \end{bmatrix} \quad (6)$$

The variance-covariance matrix of any other set of variables can be computed by applying the FOSM again [6].

3 RESULTS

The pilot area is located within a water distribution supply system that provides water to a town located in Castilla-La Mancha (Spain). The hydraulic model of the distribution system where the pilot area is located is currently being built. Apart from the model definition, this involves a socioeconomic analysis that will support the water consumption records that the water utility collects by default for billing purposes (every 3/6 months).

At the same time, sensor and mesh communication deployment are currently underway. Volume meters with a 1 litre resolution were already available in the case study area and/or being installed. These conventional volume meters have been upgraded with data loggers that record water consumption with a 1-minute time resolution, although data is sent with a smaller frequency (60 minutes) to extend battery life. Pressure and flow are also measured at the entrance to the pilot area with a 1-minute temporal resolution. The HidraIoT solution developed by Hidralab Ingeniería y Desarrollos, S.L. is being adopted for the communication technology and mesh deployment. Different temporal resolutions for the HSE output will be tested to explore the temporal resolution effect as in [19].

4 CONCLUSIONS

Hydraulic State Estimation is a powerful tool to monitor water systems, but it has only been applied to water transport networks until now in real practice. This work presents the particularities of HSE implementation in a pilot area within a distribution system in Spain. This application will enable to explore the required temporal and spatial resolution levels needed to achieve different uncertainty thresholds within the distribution level. Therefore, it will enable to fully understand flow and water quality dynamics within the pilot area, but also to identify challenges and opportunities for HSE systematic implementation in other real (and not so well-instrumented) case studies.

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