Pattern Recognition of the Household Water Consumption through Signal Analysis

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Abstract. This paper presents the initial results of a research project that aims to develop a method for losses/leakage detection and household water consumption characterization through the detailed patterns analysis of signals generated by water meters. The Department of Civil Engineering (University of Coimbra) supports the research as part of a PhD Project. An experimental facility is used for signals acquisition and data analysis will be performed by using a pattern recognition algorithm that will identify the hydraulic devices in use. It is intended to develop and test some algorithm structures at various plumbing configuration forms to find the best one. In a second phase, a consumption analysis will be carried out using that algorithm to test its efficiency in inhabited houses. The expectation is to develop an efficient water monitoring tool that helps the users to follow-up and to control the water consumption using a computer or even a mobile device.

Keywords: pattern recognition, signal processing, monitoring household water consumption, efficient water use.

1 Introduction

A household telemetry system provides a more detailed and reliable water consumption data. For this reason it is being increasingly used by water supply companies as a management tool. Telemetry systems have several advantages and due to technological innovations the deploying cost is decreasing. However, the large number of data produced by daily measurements becomes a big challenge [1]. This creates opportunities for the development of models and algorithms using that information to give a detailed analysis of consumption and enabling an efficient water management. In order to contribute with efficient tools for the water consumption monitoring and control, the main goal of this research project from the Department of Civil Engineering (University of Coimbra) is to develop a method for losses/ leakage detection and water consumption characterization through the detailed study of the signals pattern generated by water meters.

This paper presents the developments of this research, focusing on the methodology, the state of the art and the work done so far. Till now a preparatory

work on the controlled environment was carried out, including the calibration of the hydraulic system and the software development for signal acquisition, analysis and processing. After the laboratory stage we intend to analyze signals from data loggers installed in households to test and validate the new algorithms.

2. Contribution of Technological Innovation to Sustainability

During last century it has been observed that the demand of drinking water is growing faster (seven times) than the world population (four times) resulting in water scarcity risk in a several countries [2]. In Portugal, as well as in Mediterranean countries, it is estimated that in 10 or 15 years there will be lack of water quality due to the increase demand, inefficient water use and the wastewater mismanagement [3]. Annually the water losses in Portugal represent three billion of cubic meters of water and one half of this volume is lost in the urban environment, buildings and public systems of water supply [4]. The new technological tools that could contribute to the water losses control and water efficient uses are now essential to promote the water resources sustainability.

   The main contribution of this research is to propose an algorithm to analyze in real time the online signal from a single water meter at the entrance of a house that enables to identify accurately the consumption pattern of each used device. As an online monitoring tool it is expected that it could be able to detect anomalies in consumption such as losses and excessive consumption of water in a timely and reliable manner. A computer or even a mobile phone can be used to access these data and contribute to the efficient water use and conservation of water resources.

3   Water Consumption Characterization (state of the art)

The importance of detailed studies about water consumption characterization is growing due to the possibility to improve water management and its efficient use. The literature presents different methodologies for the consumption characterization. The accuracy of results varies according to each methodology, which is also reflected in the possibilities of analysis.

   Researchers from USA [5], Spain [6] and Brazil [7] present different methodologies to characterize the water consumption in households. In these three research works were used water meters with pulsed output and dataloggers for data acquisition, however, different methodologies for data analysis were developed. The TraceWizard© 4.0 software was used in [5] for the specific recognition of signals through some parameters adjustment. To allow the signals identification it is necessary to know previously a set of properties for each device (flow, volume, duration of use, and others). This enables the program to distinguish between a tap use event and a toilet flush use event and so on. If these parameters are not well-adjusted, it is not possible to do the correct identification. When three or more events occur simultaneously it may not be possible to accurately disaggregate all end uses.

In [7], the pulses were converted into flow rate (l/s) to be possible to plot consumption graphs (flow vs. time). These graphs (representation of the water consumption signals) were correlated with time using the information of each device (supplied by users). This correlation enabled to identify accurately the signals of some uses, but, due to the low accuracy of the provided information, some of the intakes had to be estimated. In [6], the information provided by the signal pulses was compared with the previous characterization of its amplitude and temporal patterns, which enabled to identify the water use in each moment. The low level of detail provided by that research report did not allow to estimate the methodology accuracy.

Studies [8] and [9] used a water meter on each hydraulic device and in the inlet pipe supply to guarantee good accuracy in the characterization phase. Despite the accuracy of the information, such methodology would be difficult to apply in inhabited buildings due to the work needed on the pipe supply installations. This situation does not have technical and economic viability in most of the situations.

4   Methods

The main goal of this study is to develop algorithms that make the pattern recognition of the water consumption behavior in each device using the data from the water meters at the inlet pipe. Experimental tests with controlled conditions were made to explore the several possibilities for setting up the facilities and to test algorithms. The steps of the experimental tests were: i) to build an experimental facility, ii) to calibrate the hydraulic system iii) to acquire the signals, iv) to store the signals, v) to process the data, and vi) to develop the algorithms for the water consumption pattern recognition.

Digital signal processing tools such as deconvolution algorithms [10] are used to data processing, aiming to solve the overlap of the signals coming from the simultaneous use of several devices in the hydraulic system. After that, techniques for feature extraction and classifiers to identify the signals of each flow classes in their respective equipment will be implemented and tested.

It is proposed to apply a feature extractor and a signal pattern recognition classifier to develop the algorithm according to the equipment studied. The features can be extracted in time or frequency domain. It is expected that the temporal or frequency characteristics of the transient response of the hydraulic system to the activation of a hydraulic devices vary according to their characteristics and their positions in the hydraulic supply system. This implies the need of a distinct signature requirement for each device even if we only have the flow rate signal in the pipe supply as an input for the classifier. It is expected that the algorithm compares the signal with the prototype generated for each device until the identification process is complete.

After the conclusion of the research in a controlled environment it is intended to carry out the data consumption analysis from inhabited houses to test and validate the algorithm. The data signals from the intake will be analyzed for one year, covering the four seasons.

5   Preparation of the Experimental apparatus

The considered hydraulic system includes two volumetric water meters with pulsed output (Actaris Aquadis +, class D) and two taps. The counted volume is converted in a pulse sequence through a sensor (Cyble™ Sensor) installed on the water meter. A data acquisition card with USB interface (USB card NIdaq 6009 data acquisition - DAQ) interconnect the Cyble™ Sensor and the laptop. This card allows the data acquisition through various analog input channels and stores the data using MatLab/Simulink® software. Some features were developed in Simulink® for data acquisition and processing enabling the analysis and development of classification algorithms based on the flow rate signal.

In future developments a pressure transducer will be used in this experimental facility to check how changes in pressure within the pipe can affect the signals characteristics. Furthermore, the localized head losses will also be studied since, theoretically, these losses also interfere with these signals.

6   Tools for Data Acquisition and Signals Analysis

The low-frequencies (LF) signal transmitted by the Cyble™ Sensor detects each rotation[1] of the water meter and then it emits 1 pulse per revolution. It remains active whenever there is a flow, whatever the flow direction is. Each sensor is connect to an analog input (AI) channels of the DAQ card using a two wired cable. After the analog-to-digital conversion (ADC) in the DAQ card, the data in digital format is send to the computer through a USB cable.

To make sure that a discrete signal is representative of an analog signal, it is required to verify the Nyquist–Shannon sampling theorem [11] which says that the sampling rate must be greater than twice the highest frequency of the signal. In this case, to allow the identification of each water meter transition, whenever it counts one volume, having been considered in the experiments a sampling frequency of 50 samples/sec.

The functionalities for data collecting and processing at the computer were developed in MatLab/Simulink® which is a commercial tool for modeling, simulation and analysis of dynamic systems. Simulink® tool uses a graphical representation of blocks as the main interface, as well as a customizable set of block libraries. It offers integration with the rest of MatLab® and it is widely used in control theory and digital signal processing for simulation of systems in various domains [12].

The data acquisition block with multiple analog input channels was used as interface in the Simulink® model. The water meter signals were connected to two input channels and they are represented by the signals HWChannel0 and HWChannel1, as shown in Fig. 1. Output blocks for data storage in the Matlab® workspace (pulse signals) and a Scope block (to show the signal during the data acquisition) were also considered. To distinguish the signals from the water meters, the analog output block generates two different values for the reference voltage of each pulse signal (3.5V and 2.5V for the signals from the water meter 1 and 2,

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[1] In each rotation pass through the water meter 0.1 litre of water.

respectively). A clock block was considered to generate the current simulation time. The Simulink® data acquisition block was configured selecting the channels involved (channels 0 and 1), the sampling frequency (50 samples/s) and the number of samples provided by the DAQ for each channel (at least 2 samples per channel).
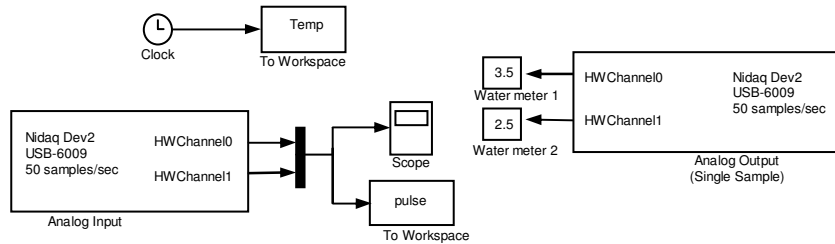

Fig. 1. Simulink® Data Acquisition Model.

Given that the DAQ card sends pairs of samples to the computer, it was necessary to develop a MatLab® function to arrange data sequentially according to the sampling time. Until this point the signals are acquired as data pulses. However, to enable the signal analysis using pattern recognition it is necessary to convert them to discrete time flow rate signals. Therefore, another Simulink® model was developed to convert data pulse in data flow rate (Fig. 2).
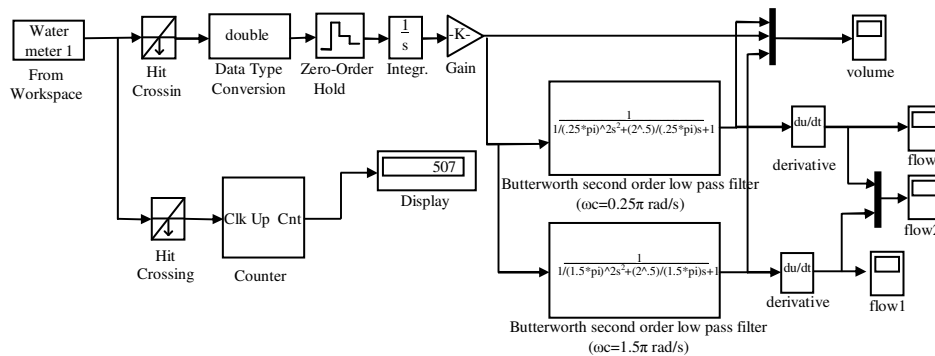

Fig. 2. Simulink® volume and flow rate calculation model.

After reading the pulses from the MatLab® workspace, they are counted through the "hit crossing" block. The "hit crossing" block detects when the input signal reaches the parameter value (0.1) in the direction specified (falling) and output 1 in the crossing time. The "counter" block counts how many times the parameter value is reached and presents it in display. The "data type conversion" block converts the input data to a suitable data type for integration and the "zero order hold" block converts the discrete-time signal to a continuous-time signal. The volume is

calculated trough the "integration" of the data pulse considering a 0.1 liters and 50 samples/sec as a "gain". The volume (Fig.3), flow (Fig.5), flow1 (Fig.4) and flow2 blocks plot the signals resulting from the simulation process.

A low-pass filter was used to cut unwanted frequencies and to smooth the graph of volume (stairs shape) allowing the calculation of its derivative to get the flow rate curve. The stair shape of the volume graph arises due to the sequence of discrete values generated by the rotating piston of the volumetric water meter (fig.3). A second order Butterworth low-pass filter with cutoff angular frequencies (ωc) of 1.5π rad/s and 0.25π rad/s were used. The transfer function $H(s)$ used in this filter is given by:

$$H(s) = \frac{1}{\left(\left(\frac{1}{\omega c} \right)^2 s^2 + 1{,}4142 \left(\frac{1}{\omega c} \right) s + 1 \right)} \tag{1}$$

After the application of the filter, smoother curves were obtained as seen in Fig. 3. With the derivative calculation it was possible to obtain the corresponding flow rate signal.
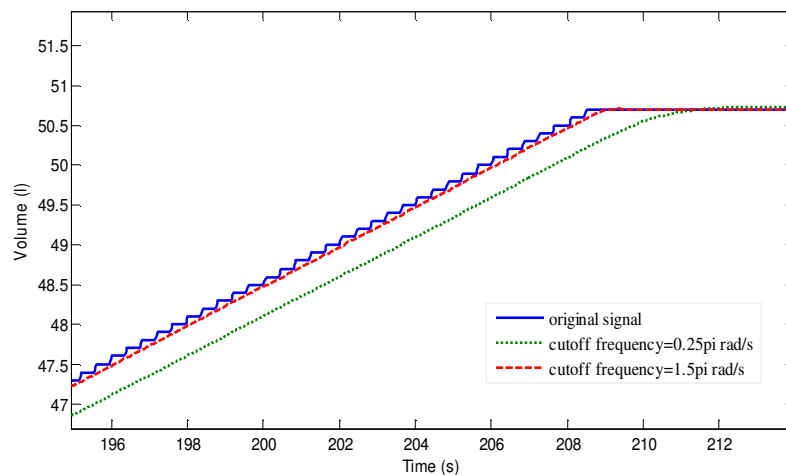

Fig. 3. Volume graph with application of low-pass filters.

Although the values of the resulted chart using the low-pass filter with 1.5π rad/s cutoff angular frequency are close to the original values of the volume graph, it still keeps some frequency components that interfere with the corresponding flow rate signal (Fig. 4). The filter with 0.25π rad/s cutoff angular frequency provides smoother curves highlighting their characteristics (Fig. 5).
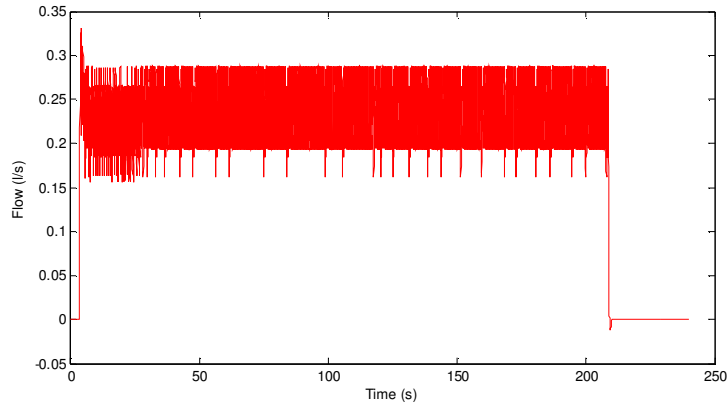
Fig. 4. Flow rate graph using a low-pass filter with 1.5π rad/s cutoff angular frequency.
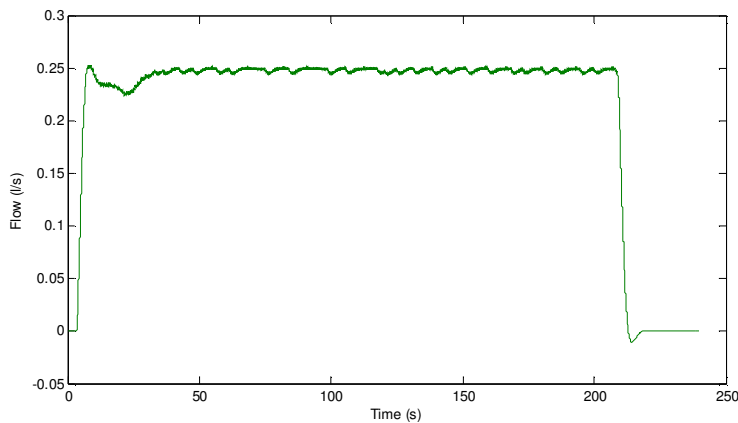

Fig. 5. Flow rate graph using a low-pass filter with 0.25π rad/s cutoff angular frequency.

Comparing the volumes recorded in the water meters with those obtained by the models developed in MatLab/Simulink® it was observed that the values are similar. Therefore, it can be concluded that the developed models are adequate to the goals.

7   Final Considerations

Until now the work was mainly focused on the experimental facility preparation, on the hydraulic system calibration and on the software development for signal acquisition, analysis and processing. The results obtained so far are considered satisfactory, since the equipment installed and the tools developed are in full operation, meeting the objectives. The next goal is to analyze a variety of hydraulic flow rate signals in different configurations considering a feature extractor. Based on

this analysis, pattern recognition algorithms will be developed, where those with the highest number of hits will be chosen. After the laboratory stage it is intend to use dataloggers installed in inhabited houses to acquire signals to test and validate the algorithm in a real environment.

It is expected that the results of this research will be considered as a relevant improvement for an efficient control of water consumption using a computer or even a mobile device that can be followed by users in any period of time (hourly, daily, weekly, …). It is also expected that unnecessary expenses, resulting from water losses, like leaks or ruptures, or water overuse, will be identified, developing, for instance, a personal water consumption monitoring system or even an automatic system to generate alarms whenever an abnormal consumption pattern is detected.

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