Expert Systems with Applications 41 (2014) 342–356

Contents lists available at ScienceDirect

Expert Systems with Applications

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

An autonomous and intelligent expert system for residential water end-use classification

Khoi Anh Nguyen [a], Rodney A. Stewart [b,*], Hong Zhang [a]

[a] Griffith School of Engineering, Griffith University, Gold Coast Campus, Australia
[b] Centre for Infrastructure Engineering and Management, Griffith University, Gold Coast Campus, Australia

ARTICLE INFO

Keywords:
Water end-use event
Water micro-component
Residential water flow trace disaggregation
Hidden Markov Model
Dynamic time warping algorithm
Gradient Vector Filtering
Adaptive analysis
Adaptive function
Water demand management

ABSTRACT

Intelligent metering technology combined with advanced numerical techniques enable a paradigm shift in the current level of water consumption information provision that is available to the customer and the water business. The aim of this study was to develop an autonomous and intelligent system for residential water end-use classification that could interface with customers and water business managers via a user-friendly web-based application. Water flow data collected directly from smart water meters includes both single (e.g., a shower event occurring alone) and combined (i.e., an event that comprises several overlapping single events) water end use events. The authors recently developed intelligent algorithms to solve the complex problem of autonomously categorising residential water consumption data into a registry of single and combined events using a hybrid combination of techniques including Hidden Markov Model (HMM), Dynamic Time Warping (DTW) algorithm, time-of-day probability functions, threshold values and various physical features. However, the issue still remained, which is the focus of this current paper, on how to integrate self-learning functionality into the visioned expert system, in order that it can learn from newly collected datasets from different cities, regions and countries, to that collected for the training data. Such versatility and adaptive capacity is essential to make the expert system widely applicable. Through applying alternate forms of HMM and DTW in association with a frequency analysis technique, a suitable self-learning methodology was formulated and tested on three independent households located in Melbourne, Australia with a prediction accuracy of between 80% and 90% for the major end-use categories. The three principle flow data processing modules (i.e., single and combined event recognition and self-learning function) were integrated into a prototype software application for performing autonomous water end-use analysis and its functionality is presented in the latter sections of this paper. The developed expert system has profound implications for government, water businesses and consumers, seeking to better manage precious urban water resources.

1. Introduction

Following a long-standing drought for the second half of the last decade across most of Australia, most capital cities introduced a portfolio of water demand management strategies and constructed capital intensive rain-independent bulk supply sources to ensure the provision of a secure water supply (Willis, Stewart, Panuwatwanich, Capati, & Giurco, 2009a). Residential water consumption is often dependent on the water using fixtures or appliances within a dwelling, the household makeup, the regional location and a plethora of socio-demographic influences. A study of end-use water consumption aids water planners and consumers to identify where and when water is used in a household and hence, assists in driving proactive reductions in consumption (Loh & Coghlan, 2003; Makki, Stewart, Panuwatwanich, & Beal, 2011; Stewart, Willis, Giurco, Panuwatwanich, & Capati, 2010). However, the existing water end-use classification techniques require an extensive use of human resources to collect a combination of water use behaviours and appliance/fixture stock inventory data through a household audit followed by 2–3 h of analyst time for each home (Beal & Stewart, 2011; Stewart, Willis, Panuwatwanich, & Sahin, 2011). Presently, water end use or micro-component studies are restricted to the research domain, since it is not economically viable to complete citywide studies due to resource intensity of the flow data classification process. Intelligent and autonomous end use classification firmware is required along

* Corresponding author. Address: Centre for Infrastructure Engineering and Management, Griffith University, Gold Coast Campus, Queensland 4222, Australia. Tel.: +61 75552 8778.

E-mail addresses: k.nguyen@griffith.edu.au (K.A. Nguyen), r.stewart@griffith.edu.au (R.A. Stewart), hong.zhang@griffith.edu.au (H. Zhang).

0957-4174/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.eswa.2013.07.049

with bold large-scale roll-outs of high commercially available high resolution smart water meters in order to bring this level of water consumption information to the masses. Currently, an increasing number of smart water metering technologies have been introduced to the market. Such metering devices embrace two distinct elements: meters that use new technology to capture water use information and communication systems that can capture and transmit real-time water use information (Stewart et al., 2010). These forms of smart metering technology can provide total consumption data to the customer and utility at high levels of resolution; however, they fail to disaggregate this data into its end-use use categories.

In the present study, an attempt to automate the domestic water end-use classification process and, thus, to enhance current practices in the urban water industry is required, and a robust hybrid model that employs HMM, DTW and event probability techniques is developed. The proposed system will allow individual consumers to log into their user-defined water consumption web page to view their daily, weekly, and monthly consumption tables as well as charts on their water demand across major end-use categories (e.g., leaks, clothes washer, shower, irrigation). This system can rapidly alert customers of leak events so that they can immediately be addressed rather than waiting for the present slow feedback process from the traditional metering technology (e.g., the quarterly bill). The system will also benefit water businesses by rapidly providing water end-use reports of any desired property or suburb, thereby empowering them to develop more targeted conservation programs in water scarcity periods (e.g., Willis, Stewart, Giurco, Talebpour, & Mousavinejad, 2011b; Willis, Stewart, Panuwatwanich, Williams, & Hollingsworth, 2011a), improved water demand forecasting (e.g., Makki et al., 2011) and optimised pipe network modelling (e.g., Beal & Stewart, 2013; Carragher, Stewart, & Beal, 2012). Fig. 1 summarises below the three key stages in the development of this system:

- Stage 1: Develop a non-adaptive intelligent model that autonomously disaggregates collected water flow trace signatures that were collected from the intelligent water meters into a categorised registry of water end-use events (Nguyen, Zhang, & Stewart, 2013a,b).
- Stage 2: Equip the model with adaptive capabilities that enable it to interpret untrained water end-use signature traces, thereby allowing it to adapt to new situation context (e.g., different city to training dataset).
- Stage 3: Develop an intelligent and user-friendly expert system and prototype firmware for use by consumers and businesses.

2. Background

2.1. Existing water metering process and new paradigm

Water consumption readings are usually recorded manually on a quarterly or half yearly basis. Under most situations, a whole year's worth of water consumption data is described by only two to four data points in the water businesses billing system. Conventional water meters count each kilo litre of water as it passes through the meter and do not have the ability to record when (i.e., the time of day) and where the consumption takes place (e.g., washing machine, leaks) (Stewart et al., 2011). These systems produce limited and delayed water consumption information. The current water metering system does not typically provide real-time or continuous/frequent water consumption data, and in cases where it does, it does not provide a sufficient level of data resolution to allow water end-use event categorisation. While real-time or near real-time water consumption data provisioning is now commercially viable with current smart metering technology, there is presently no firmware that can autonomously disaggregate this flow data into the 'richer' water end use categories of consumption. Until, such firmware is developed, powerful water end use information will be contained to expensive research studies (e.g., Beal & Stewart, 2011).

2.2. Intelligent system development using various pattern recognition techniques

To overcome these limitations, intelligent metering technology is united with advanced pattern recognition techniques to enable a paradigm shift in the current level of water information provision available to the customer and water business. The aim of this project is to develop an autonomous and intelligent system for residential water end-use classification through the employment of various mathematical techniques, namely HMM, DTW and frequency analysis as presented below.

A Hidden Markov Model (HMM) is a statistical Markov model in which the system being modelled is assumed to be a Markov process with unobserved (hidden) states. An HMM can be considered to be the simplest dynamic Bayesian network, which is one of the most popular techniques in the field of hand writing and speech recognition (Ephraim & Merhav, 2002). Principal theories and typical applications of this technique have been presented in Baum and Petrie (1966), Starner and Pentland (1995), Baum, Petrie, Soules, and Weiss (1970), Cho, Lee, and Kim (1995), Ghahramani

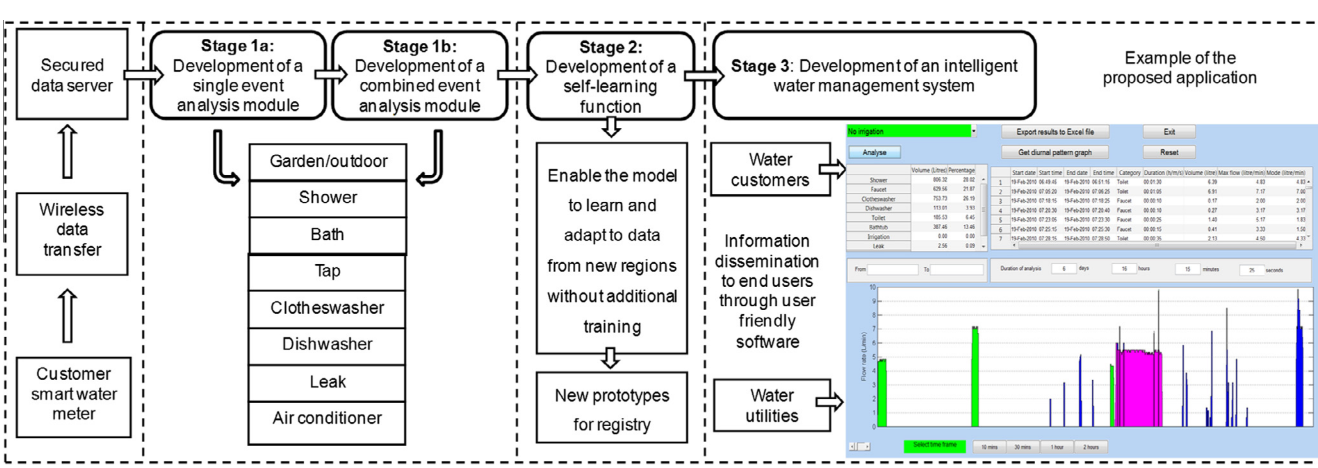

Fig. 1. Overview of proposed autonomous and intelligent water management system.