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Mobile sensor networks for optimal leak and backflow detection and localization in municipal water networks

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ABSTRACT

Leak and backflow detections are essential aspects of Water Distribution Systems (WDSs) monitoring and are commonly fulfilled using approaches that are based on static sensor networks and point measurements. Alternatively, we propose a mobile, wireless sensor network solution composed of mobile sensor nodes that travel freely inside the pipes with the water flow, collect and transmit measurements in near-realtime (called sensors) and static access points (called beacons). This study complements the tremendous progress in mobile sensor technology. We formulate the sensor and beacon optimal placement task as a Mixed Integer Nonlinear Programming (MINLP) problem to maximize localization accuracy with budget constraint. Given the high time complexity of MINLP formulation, we propose a disjoint scheme that follows the strategy of splitting the sensor and beacon placement problems and determining the respective number of sensors and beacons by exhaustive search in linear time.

1. Introduction

Drinking water supply for about 90% of U.S. population comes from nearly 170,000 public water distribution systems (WDSs) (Copeland and Tiemann, 2010). Spanning close to a million miles, the aging, buried pipeline infrastructure (U.S. Evironmental Protection Agency(a); American Water Works Association, 2013 (a)) plays an important role in maintaining and preserving a clean and reliable water supply essential to industrial growth and public health. Since many main pipes in the urban infrastructure are reaching the end of their life and may easily date back to the early 20th century, they are highly vulnerable to breaks and leaks. This has been manifested recently by an approximately 237,600 water main breaks per year in the U.S. causing a loss of nearly $2.8 billion (U.S, Evironmental Protection Agency(b)). Breaks in water mains pose two key threats: (i) loss of water, service disruptions, and structural damages due to leakage; and (ii) public health risks due to backflow events.

Leakages

Water demand needs are getting tighter over time, especially with the recurrent, escalating droughts throughout the past decade (Mortazavi-Naeini et al., 2015). In such stressful scenarios, water leakages are costly. A large percentage of the estimated 48.6 billion cubic meters water lost worldwide every year is due to leakages in water pipes (Thornton et al.). Water leakage causes severe economic losses by means other than the loss of water too, such as ground instabilities, transportation disruptions, and problems to communication lines (Meseguer et al., 2014).

Backflows

A backflow is an unwanted flow of non-portable water, or other substances such as soil, pesticides, etc., into WDS pipelines. Backflow events occur when there is a reverse pressure gradient at cross-connections, and are caused by cracks, breaks, or loose connections. Such events cause illness and are a major threat to public health (Furnass et al., 2013; Rasekh and Brumbelow(a)). This is evident from a U.S. EPA compilation, which states that between 1970 and 2001, 459 incidents led to an estimated 12,093 illnesses (U.S Environmental Protection Agency(c)).

The economic and health impacts of leaks and backflows

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warrants the replacement of worn out systems. However, the American Water Works Association's report (American Water Works Association (b)) estimates that over the next 30 years, $250 billion may be required. For efficient replacement of the aging water pipes, the conditions of the pipeline system, such as location of breaks, cracks, loose connections are required.

1.1. State of the art

There exist several methods based on various operating principles for detection, localization, and pinpointing of leakages in municipal water distribution systems. Water audits based on metering and water balance calculations can be performed to quantify water losses and provide an extremely crude approximation of the location of losses. A better estimation is achieved through step-testing method whereby valves are systematically closed to subdivide the area and localize the leakage.

A comparatively more recent leak localization method is acoustic logging, which is performed using hydrophones or vibration sensors (Hunaidi et al., 2004). Ground penetrating radar is employed to localize the leaks by virtue of detecting underground voids caused by leakage water flow in the immediate vicinity of pipes. More accurate leakage localization, which is also referred to as leakage pinpointing, may be achieved using leak noise correlation, tracer gas, and pig-mounted acoustic techniques. Detailed description and comparison of these well-known methods for detection and pinpointing of leaks may be found in (U.S. Environmental Protection Agency(b); Puust et al., 2010; Chatzigeorgiou). An approach towards optimal surveillance monitoring is a method that maximizes the value of information (Convertino et al., 2014) to optimally place observers that detect outbreaks as they spread. However, our leak/backflow detection model is different since the sensors are mobile, and the event does not propagate, whereas in (Convertino et al., 2014), the event propagates while observers are static.

The application of inline, mobile sensors technology for leakage pinpointing has attracted a lot of attention by both researchers and practitioners during the recent years (Pure Technologies (b); Chatzigeorgiou; Lai et al., 2010; Suresh et al., (a); Suresh et al., 2012; Suresh et al., (b); Suresh et al., 2014a; Suresh et al., 2014b; Banks et al., 2012). These are small monitoring devices that traverse freely with the water flow inside the pipes. The sensors can collect measurements from the environment and also process them and transmit the processed data to access points placed outside the pipelines. They have achieved popularity recently thanks to their unique abilities in collecting spatially high resolution data. Simple acoustic sensors are already being employed in real WDSs for leak detection (Pure Technologies (a); Canadian commercial newswire) and new sensors are under test and evaluation for monitoring water quality parameters in near-realtime scales (Banks et al., 2012).

Deployment of mobile sensors may happen on-demand by a utility manager as part of a periodic system monitoring or be triggered when the presence of a leak/backflow is suspected with the help of a static sensor system or by complaints from consumers. They have been already applied to water utilities of several cities around the world, including Dallas, Montreal, and Manila (Pure Technologies (a)). Their increasing popularity is presumably associated with their ability to pinpoint the leaks more accurately than other existing methods without causing any disruption to regular water utility service. Table 1 contains most of the existing practical solutions that use mobile sensors for leak/backflow detection in WDSs.

Although inline, mobile sensors for pinpointing leakages have been already designed and fabricated, decision support models to facilitate and enhance their operation through simulation of their movement in the pipelines network and optimization of their application is still underdeveloped. Development of such computational models is a major focus of this study.

A recent work (Perelman and Ostfeld, 2013) examines the deployment of mobile water quality sensors along with static water quality sensors for contamination detection. The paper demonstrates the improvement in detection rate provided by mobile sensors in conjunction with static sensors. However, the movement of the sensor is modeled to move through a deterministic path, provided the flow velocities in the pipes are known. The model use is also limited to contamination event detection and is not developed to enable source localization as well. In this paper, we consider leak/backflow detection, which requires a more stringent sensing model where the mobile sensors require to move close to the leak points to enable detection and localization. In reality, mobile sensors move randomly through the pipes with a probability distribution at each junction which has not been yet considered in existing solutions in the literature. The sensor mobility model in this paper is more general to accommodate the random movement of sensors at junctions. This way, the sensors mobility may be modeled more accurately and thus be deployed more efficiently and effectively.

Other solutions to monitor pipelines using mobile sensors are presented by the research community (Kim et al., 2010; Lai et al., 2012; Sun et al.). TriopusNet (Lai et al., 2012) is a solution for autonomous continuous monitoring of pipelines. The solution however assumes that the path of a sensor can be made deterministic by controlling the flow of water, which is impractical without disrupting the function of the WDS. MISE-PIPE (Sun et al.) is another similar system based on magnetic induction in underground pipes. Theoretical results in pipeline monitoring using mobile sensors have also been studied (Yazdani and Jeffrey). performs a mathematical analysis of sensor placement and presents analysis of complex networks using graph-theoretic concepts (Li et al., 2012). addresses the gallery guarding problem that requires every point in the pipe to be monitored by a robot. However, these problems are specific to controlled mobile devices. The problem of ensuring k-coverage in scenarios similar to the one we consider is presented in (Xiong et al., 2012). However, the coverage requirement is different, and mobility is ignored.

1.2. Our contributions

Recent work in WDS monitoring using mobile sensors of notable interest are (Suresh et al., (a); Suresh et al., 2012; Suresh et al., (b)), which tackle the problem of optimizing the number of sensors required to cover a region of interest in the WDS with a required degree of coverage. The papers also present a source identification technique, referred to as localization, to obtain accurate location of leaks/backflows using beacons placed outside the pipeline. We refer to the problem of optimal sensor placement as the Minimization of the Number of Sensors problem (MNS). The papers (Suresh et al., (a); Suresh et al., 2012; Suresh et al., (b)) consider sensor and beacon placement as disjoint problems. Sensor placement to achieve a required sensing coverage is seen as requirement for localization and beacon placement problem is solved independent of sensor placement under the assumption that sensing coverage is ensured. The problem of sensor placement that obtains the optimal placement of sensors, given an upper bound on the total number of sensors has been tackled previously (Suresh et al., 2014a). A simulator called FlowSim is developed and used for the evaluation of the system.

Computer models have been previously developed for the use of mobile sensors in the detection of contaminant intrusion events in