WaterBox: A Testbed for Monitoring and Controlling Smart Water Networks

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ABSTRACT

Smart water distribution networks are a good example of a large scale Cyber-Physical System that requires monitoring for precise data analysis and network control. Due to the critical nature of water distribution, an extensive simulation of decision making and control algorithms are required before their deployment. Although some aspects of water network behaviour can be simulated in software such as hydraulic responses in valve changes, software simulators are unable to include dynamic events such as leakages or bursts in physical models. Furthermore, due to safety concerns, contemporary large-scale testbeds are limited to the monitoring processes or control methods with well established safety guarantees. Sophisticated algorithms for dynamic and optimal water network reconfiguration are not yet widespread. This paper presents a small-scale testbed, WaterBox, which allows the simulation of emerging/advanced monitoring and control algorithms in a fail-safe environment. The flexible hydraulic, hardware, and software infrastructure enables a substantial number of experiments. On-going experiments are related to in-node data processing and decision making, energy optimization, event-driven communication, and automatic control.

1. INTRODUCTION

In the last decade, there has been a growing trend for water utilities to create smart water networks aiming to improve quality of service and reduce water waste and maintenance costs. In order to achieve these goals, traditional water networks have been augmented with sensor nodes and data loggers which enable monitoring by transmitting the network state periodically to data centers. Anomaly detection and demand prediction algorithms [13, 1, 18, 22, 11] utilise this information to enable the optimal reconfiguration of water network assets such as Pressure Regulating Valve (PRV) states and pump scheduling. These decisions are vital and therefore extensive simulation of algorithms is necessary before final deployment in real water distribution networks.

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As a perfect example of Cyber-Physical Systems (CPSs), both the physical and computational elements of smart water networks require simulations. However, software simulators can cover either water network behaviour [17] or wireless sensor network features [6]. Even in [12], where outputs of hydraulic simulations [17] are combined with Matlab algorithms were insufficient to reproduce issues that arise in real systems; examples are pipe burst or leakage, sensor malfunctions, communication interruptions or dropouts. For these reasons, large scale testbeds have been created to allow researchers to test novel control algorithms real conditions. For instance, in the WaterWise project [2], a testbed with 25 sensor nodes has been deployed in Singapore's water network. These sensor nodes transmit high sample rate flow and pressure data in 30-second and 5-minute intervals respectively through 3G or WiFi to a server which then analyses the data. Similarly, in our parent project, a 'smart water networks demonstrator' with 24 sensor nodes has been deployed in parts of an operational network (see Fig. 1) to evaluate sensing, data acquisition, analytical and control technologies, to assess the operational benefits of dynamic District Metered Areas (DMAs[1]) [21] and facilitate testing of communication algorithms. In contrast to [2], our current algorithms address smart water networks from a different perspective by introducing concepts such as in-node data processing and decision making, energy optimization, event-driven communication, and automatic control.

Automatic control methods are vitally important to solving some operational challenges like reducing pressure driven leakage, energy usage in pumping, leak localization etc. However, a naive deployment of new control technologies in critical infrastructure and their potential failures may have catastrophic consequences for large scale operational testbeds. Two of the few sophisticated operational control systems include i^{2}O [8] and Derceto [5], who have developed and applied 'optimal' automatic remote control of PRVs and pumps, respectively. However, these systems are based on diurnal training that produces static control schedules for predefined periods of time. Such methods have a limited capacity to respond to disturbances to the system in real-time, which can make their operations suboptimal. In this project, we study and develop real-time control algorithms, that have

[1]This is a defined area of the water distribution system that can be isolated by valves and for which the quantities of water entering and leaving are measured/metered.

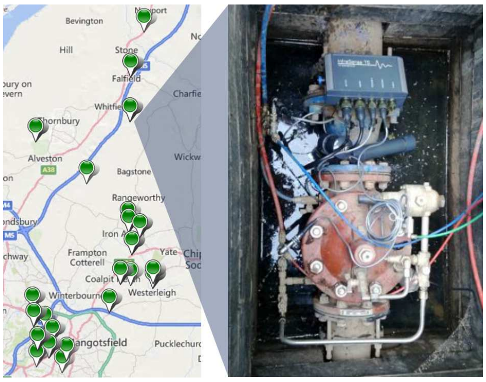


Figure 1: Large scale testbed and sensor node hardware.

feedback from sensors and aim to respond to anomalies, demand changes, and reconfiguration in an optimal fashion. Thus, the construction of a user friendly small scale testbed infrastructure in a fail-safe environment to efficiently develop, deploy and debug applications and algorithms is essential.

In this paper, we discuss our testbed, WaterBox, which simulates monitoring and control processes for smart water networks. The main benefits of this testbed are as follows:

- It allows us to simultaneously study water network and sensor network limitations. The testbed makes it possible to mimic faults, failures and constraints such as leakages and burst, communication issues, resource constraints (i.e. power, memory), and delays in time sensitive control processes.
- In addition to enabling developers and engineers to simulate real scenarios (eg. multi-feed DMAs), it supports easy installation, assembly, adaptation, and reconfiguration of water network topology and computing and communication elements.
- It enables computer scientists to better understand the physical system and facilitates the cooperation with civil engineers. Furthermore, it enhances the teaching of Cyber-Physical Systems.
- Cutting edge technologies are utilized by allowing the development of next generation water network sensor nodes, algorithms and the coexistence of multiple communication modules.

The rest of this paper is organized as follows. Section 2 describes the design overview of the testbed and simulation processes for real scenarios. Section 3 analyzes the hardware and software infrastructure. Section 4 presents preliminary experiments. Section 5 will conclude the paper.

2. DESIGN OVERVIEW

A DMA-based water supply network structure consists of three individual layers (Fig. 2): (a) storage and pumping, (b) supply zones and DMAs, and (c) end users (customers). While valves control flows and pressures at fixed points in the water network, pumps pressurise water to overcome gravity and frictional losses along supply zones, which are divided into smaller fixed network topologies (in average 1500 customer connections) with permanent boundaries,

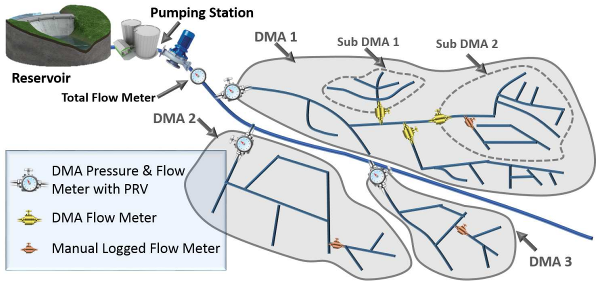


Figure 2: DMA-based water network architecture.

District Meter Areas (DMAs). The water pressure distribution and flows into each DMA is continuously monitored with the aim to enable proactive leakage management, simplistic pressure management, and efficient network maintenance. For more accurate results, contemporary strategies implement DMAs in even smaller areas so-called sub-DMAs with in average 500-1000 customer connections.

Operational control problems include optimisation based pump scheduling and valve operation. For a network with given demand patterns, we determine a control sequence for pumps and valves, over a certain time horizon into the future (often 24 hours). This is done in order to minimize pumping costs and reduce leakage while satisfying customers' demands with sufficient hydraulic pressure. In most water distribution systems, the pumping of treated water from reservoirs to supply zones and storage tanks consumes most of the energy budget for a utility. For example, by a clever use of the storage tanks and reservoirs, pumping schedules can be shifted to cheap tariff periods resulting in significant savings [15, 20]. Such pump scheduling are particularly challenging because the associated mathematical optimization problems combine integer variables (pump ON/OFF) with continuous nonlinear constraints of nodal pressures and pipe flows; these result in optimization problems of Mixed Integer Nonlinear Programming (MINLP) type. Since the difficulty in solving MINLP problems scales prohibitively large with problem size, such approaches cannot be used in a near real time operational setting for large scale water networks. In [20] and references therein, the problem can be approximated by one that finds optimal reservoir trajectories. A much smaller global optimization method can then be solved for each pumping station to find efficient pumping schedules that give rise to the already computed optimal trajectories. Our work studies the performance of stable new control methods that track optimal reservoir level trajectories in the presence of disturbances and measurement noise; concepts that will be tested on WaterBox include, centralised and distributed controllers, communication energy minimizing protocols, efficiency of different controllers under disturbances, etc.

One of the main objectives of this project is the investigation of optimal hydraulic and topology control of water network systems to reduce pressure for leakage and pumping cost reduction. Many studies have shown that pressure management with internal and inlet PRVs is a cost effective and efficient way to reduce leakage levels [19]. Preliminary work on adaptively reconfigurable DMAs [21] has also shown the effectiveness of aggregating DMAs into larger controlled pressure zones during 4am-2am; this is done by controlling the DMA boundary PRVs. For example, model predictive control (MPC) can be used with demand forecasts to minimise pressure, which reduces pressure driven leakage, while satisfying minimum pressure constraints at critical points in the network. These are implemented as flow-modeluation curves (outlet pressure is controlled as a function of measured flow). The use of multi-inlet DMAs, in addition to giving better pressure performance, improves the security of of supply. However, the interaction between modulating valves can cause instabilities (pressure oscilations across the network). Our objective is to study stable optimal pressure control methods for multi-inlet DMAs. The WaterBox allows us to physically simulate pressure modulating curves and their interactions.

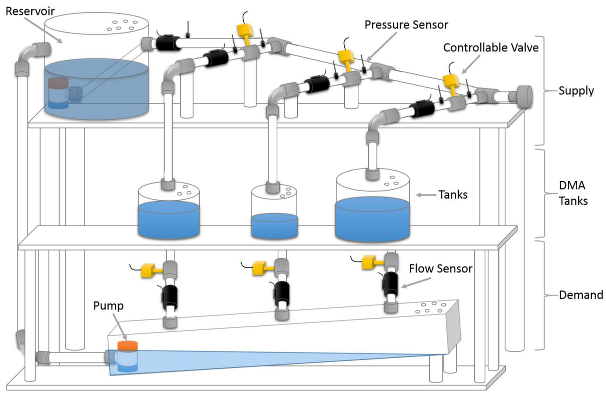
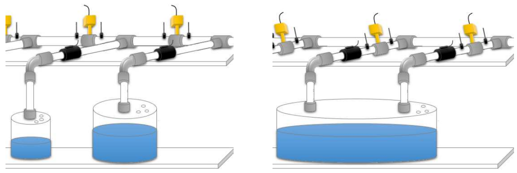


Figure 3: Testbed design overview.



(a) Sequential DMAs (b) Multi-feed DMA

Figure 4: Testbed DMA reconfiguration scenarios.

The proposed small scale testbed, WaterBox, in Fig. 3 aims to simulate a DMA-based smart water network and consists of three individual layers:

- **Supply (upper layer):** The water network backbone which simulates a reservoir, a pumping station, and three neighbouring DMA inlets that are monitored by pressure and flow sensors, and controlled by analog valves.
- **DMAs (middle layer):** DMA water volume state or DMA tank water levels with varying area sizes.
- **Demand (lower layer):** DMA water demand level which has one valve per DMA to mimic the variation of demand in time.

After the demand layer, the water is collected in a large tank and is recycled back to the upper-layer reservoir through a underwater pump. This closed loop feature supports long-term experiments without the need for water refilling.

Given the testbed's hydraulic reconfiguration feature, the decision of implementing three DMA inlets derives from the need to cover a large number of real scenarios minimizing equipment requirements. For instance, the scenario of a supply zone in Fig. 2 can be easily simulated with the configuration as shown in Fig. 3. Furthermore, more complex and contemporary topologies can be simulated such as sub-DMA (series connection) and multi-feed DMA (parallel connection) structures by changing the order of the valves as shown in Fig. 4a and Fig. 4b respectively.

3. HARDWARE AND SOFTWARE INFRASTRUCTURE

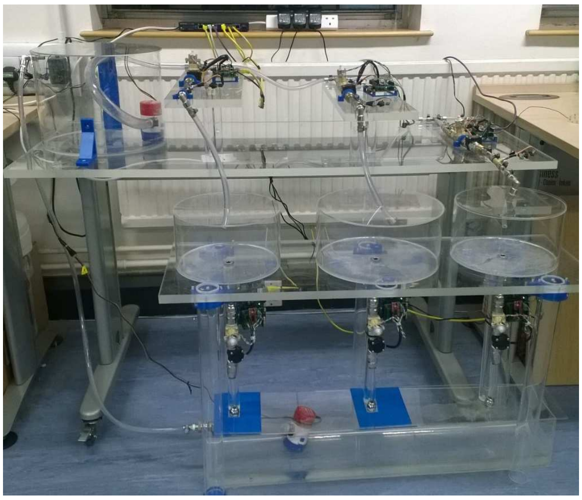


Figure 5: WaterBox.

This section describes the implementation of WaterBox (Fig. 5) focusing on the hardware and software infrastructure.

3.1 Frame and Hydraulics

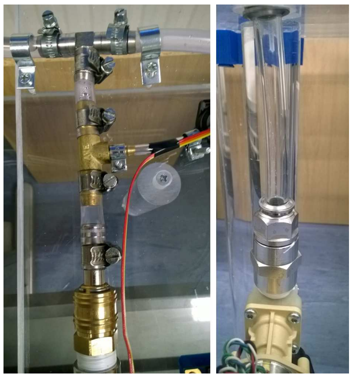


Figure 6: Hydraulics: pipes and joints.

In order to design a testbed for an in-lab environment that involves water experiments and electronic equipment, several things need to be taken into consideration. The first is the type of materials will be used to build the frame and tanks. Clear acrylic was the main material used to build the frame due to its features of waterproofness, durability, resilience, and transparency, while stable metallic legs hold the upper level of testbed. For the same reasons, the tanks and reservoir were made from clear acrylic and were shielded with heavy duty epoxy resin. To ensure the durability, the tanks and reservoir were filled with water and maintained full in a fail-safe environment for four days.

The second decision regards the size of the testbed assets. Due to in-lab space availability, the upper layer size is 135cm x 70cm x 60cm (width x height x depth) as a regular desk. By having this as reference point, the lower level selected to be 100cm x 50cm x 32cm. and cuboid tank 90cm x 15cm x 16cm. To ensure that the water volume of upper level will be less than the cuboid tank volume, the dimensions of the reservoir and three tanks is 33cm x 22cm (diameter x height) and 25cm x 14cm (for each tank) respectively. Additionally, two extra tanks (20cm x 14cm and 30xm x 14cm) were created to simulate the different DMA sizes.

After the construction of the frame and the tanks, the next step was the decision and installation of hoses and joints. The required filling time of tanks (200ml/sec), which is related to the supported water pressure and hoses diameter, was the main consideration during the decision process. The diameter of hoses are 12mm and all the joints are from stainless steel that both allow pressure up to 10 bars. Main requirement in testbed it to support visibility of water flow and thus clear flexible hoses were used. The testbed contains two types of joints (Fig. 6) for the two layers respectively: (a) couplers (quick release and regular) with nozzles binding with hose clamp and (b) pneumatic. The difference lies on the need to simulate bursts and leakages on the upper layer and to ensure stability on the lower level.

3.2 WaterBox Sensor Node

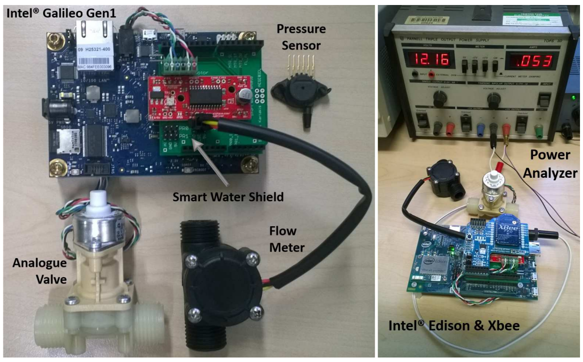


Figure 7: WaterBox sensor node and power analysis.

One of the goals of WaterBox development is to build a smart autonomous water network involving cutting-edge technologies that can be deployed to real networks. Furthermore, WaterBox should provide to researchers and developers an easy interface to implement and apply applications and algorithms referring to in-node decision making, control and communication optimization. This section describes WaterBox sensor node (Fig. 7) that allows user-friendly interaction, reconfiguration, and adaptation to simulation scenario.

3.2.1 Sensors and Actuator

Main requirement of in-lab small-scale testbeds is the existence of low power and cost sensors and actuators. WaterBox contains sensors and actuators that require up to 5V and 12V respectively and standard communication interfaces while allows the integration of other sensors as well. The basic setup of a sensor node (Fig. 7) consists of:

- **Flow Meter:** This pulse-based sensor requires 5 to 24VDC power, each pulse is approximately 2.25 milliliters. The pulse-based architecture of the sensor allow low power consumption and many contemporary systems use this type of sensor i.e. in smart grids and building power management.
- **Pressure Sensor (MPX5700GP):** This gauge-based sensor operated between 0 to 7 bars pressure, requires 5VDC power supply, and produce analogue signal which can be transformed to kPa pressure measurements by using the following calibration function: $Pressure = (((input/VIN) - 0.04)/0.0012858) + ERROR$
- **Motorized Valve:** This valve has been specifically developed for applications that require analogue, continuous and instant adjustment of the flow rate. The valve requires 12VDC power supply, interfaces over standard six-pin stepper motor interface, and remains functional in up to 3 bars water pressure.

Additionally, key aspect of this research is power analysis, thus a **power analyzer** were used. Fig. 7 presents the energy requirements of our sensor node by using as development board an Intel Edison and communication module an Xbee.

3.2.2 Smart Water Shield

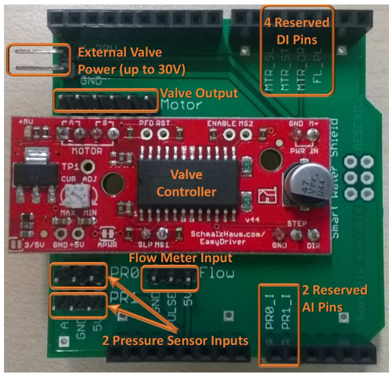


Figure 8: Smart water shield.

Main challenge of designing sensor nodes for testbeds or prototypes is the component-based development of generic interfaces between sensors and development/ boards that provide flexibility on changes. Custom-made solution are unable to support simple modifications such as the installation of a new sensor. Arduino shields [3] are boards that can be plugged on top of the Arduino PCB extending its capabilities and provides extensive flexibility to prototypes. To exploit this flexibility, we designed our custom Arduino shield based on Arduino UNO R3, Smart Water Shield (Fig. 8). Smart Water Shield reserves four digital and two analogue pins, provides one extra power input for more powerful valves (up to 30VCD), and support two pressure sensors (one per upstream and downstream), one motorized valve and one flow meter.

Another benefit of the Smart Water Shield creation is the compatibility with a large number of development boards from Arduino (or other vendors that support shields [14]) with different capabilities. This fact enables the simulation of hybrid systems where the sensor nodes have different energy consumption needs and computation capabilities. An example of a critical simulation scenario, where this feature is necessary, is the control of the water network.

3.2.3 Development Board

Contemporary sensor nodes for smart water networks embed low power micro-controllers (MCU) [7] in order to extend battery life. In spite of energy savings, these MCUs have low memory capacity and computation capabilities (i.e. [7] contains only 2KB). This limitation prohibits the deployment of sophisticated algorithms that require enough memory to analyze a small window of historical data inside the sensor nodes. In recent years, to overcome the memory and computation limitations, many research institutes and companies have released high-performance development boards, such as Raspberry Pi [16] and Intel Galileo or Edison (includes a dual core, dual threaded Intel Atom CPU at 500MHz and a 32-bit Intel Quark microcontroller at 100 MHz.)[9]. The main drawback of these boards is this high-power requirements at three orders of magnitude more than MCUs.

The solution to the above issues is impacted by the following two factors: (a) the evolution of development boards and (b) pre-existence of energy harvesting systems in smart water networks. For instance, our preliminary research on power consumption has shown that the new Intel Edison board consumes (0.053 Amp) one order of magnitude less power than the Intel Galileo Gen 1 board (0.52 Amp). Furthermore, energy harvesting data from our large scale testbed, that embeds [4] system, shows that the produced power up to 14 Watts depending on the pressure level.

Another benefit of these boards is the large variety of embedded communication modules such as WiFi, Ethernet, and Bluetooth Low Energy (BTLE). In addition, available low cost Arduino shields allow communication through Zigbee, 3G/4G, GSM etc. For example Fig. 7 (right) presents the energy consumption experiments for Intel Edison with Xbee shield. By supporting these communication modules, WaterBox enables the evaluation of hybrid systems, routing methods, and MAC protocols.

Main goal of testbeds is the convenient development of algorithms from developers and researchers with different programming backgrounds. Intel Arduino boards support operating systems such as Linux Yocto and Windows IoT. These operating systems facilitate the creation of high-level applications that include i.e. multiple threads, file system, and sockets. Furthermore, the multi-platform feature enables the use of a high-level programming languages (i.e. C/C++, Node.JS, Python) and frameworks that wrap difficult hardware details. Applications can be developed in powerful Integrated Development Environments (IDEs - i.e. Visual Studio) and debugged remotely through Ethernet or WiFi. Thus, WaterBox provides an easy, multi-platform, and flexible software and hardware environment that can handle most kinds of smart water scenarios.

4. PRELIMINARY EXPERIMENTS

This section describes the WaterBox on-going experiments

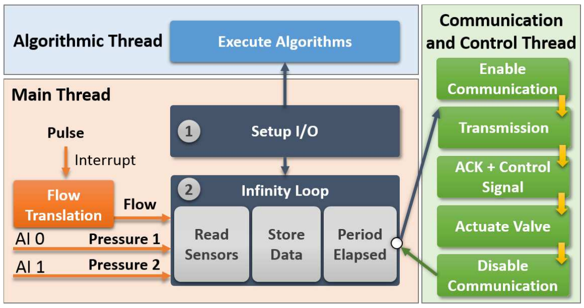


Figure 9: Experiment software infrastructure.

and presents the software architecture of the system to support them. In Fig. 5, WaterBox contains six sensor nodes, one per DMA supply and demand. Four sensor nodes consists of Intel Galileo development boards with Windows IoT which are connected to the local network through Ethernet, and two Intel Edison boards with Linux Yocto which communicate through WiFi. In order to create stable algorithms, Visual Studio was selected as development platform which allows the remote debugging. Therefor, firstly the algorithms are applied to Intel Galileo nodes and then compiled for the Intel Edison nodes.

A basic application was created to allow new users, such as researchers and students, to apply their algorithms. Fig. 9 illustrates the structure of this application. This application generates three main threads: (a) main, (b) algorithmic, and (c) communication and control. Initially, the main thread activates hardware I/O based on connected sensors and actuators. Additionally, in this phase a new thread is being activated to execute algorithms. After the setup, an infinity loop retrieves and stores measurements continuously, and fires an event periodically whenever a predefined time elapses. This event creates a new thread which enables the communication and control the valve (Fig. 9 - right).

Having this software infrastructure, our on-going experiments focus on the following categories:

In-node Decision Making: Main goal is to push the decision making such as leakage and hardware anomaly detection into the sensor nodes. This feature may allow the nodes to transmit alerts at real time without waiting for the next transmission period. [10] was the first deployed algorithm to detect anomalies by compressing data losslessly at the same time. During this deployment a number of compression algorithms were evaluated.

Control: The first set of experiments concerns the comparison of heuristic-based pump optimization with a Lyapunov stable reservoir level regulation control algorithm. The aim is to test the stability of the algorithms under communication constraints, model uncertainty and measurement errors. Other experiments test flow modulation schemes for single and multi-feed district areas.

Communication: Aim of our research is to optimize communication by transforming the traditional periodic transmission approach to event-based in smart water networks. The definition of an event constitutes our main challenge because data transmission delays and control signals' calculation may result leakages and bursts. In order to ensure local stability and to optimize the communication we define the events based on the results of control experiments (i.e. control function, stability bounds). Furthermore, by exploiting the ability of sensor nodes to support multiple communication media, experiments based on the benefits of hybrid and opportunistic networks are being conducted.

Power Consumption: Energy consumption is vital for sensor nodes and depends on the algorithms' complexity, communication frequency, and sensor sampling. Therefor, at any aforementioned experiment type, power consumption is main metric that is being evaluated.

5. CONCLUSION

In this paper, we present the development of a small-scale testbed, WaterBox, that simulates smart water networks and enables the evaluation of in-node decision making, energy optimization, automatic control, and event-driven communication algorithms. In order to simulate a real DMA-based water network, we created an acrylic structure combined with hydraulic components that allow reconfiguration and anomaly scenarios representation (leakages and bursts). To create a flexible hardware infrastructure, we designed an Arduino-based shield, Smart Water Shield, that provides a clear interface among development boards, sensors (i.e. pressure and flow), and actuators (i.e. valves). The selected high-end development boards (Intel Galileo and Edison) support a multi-platform, multi-threaded, and user-friendly development environment, which allows the easy use for researchers and students. To provide further development enhancements, we provide a fundamental software application which utilizes the hardware capabilities and procures an extendable programming template. After initial evaluation on WaterBox, the algorithms are being deployed on our large scale testbed and are being tested under real situations. Currently, we are working to extend our testbed by applying more complex algorithms including new scenarios such as security, and new sensors such as water quality.

6. ACKNOWLEDGMENTS

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