An Integration Platform for Smart Waste-Water Infrastructures

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***Abstract*—Water utility companies face increasing economic and environmental pressures to optimise their infrastructure, in order to save energy, mitigate extreme weather events, and prevent water pollution. One promising approach consists in using better distributed control (smart systems) in water networks. These systems are however difficult to build, and go well beyond the traditional expertise of water companies. In this paper, we argue therefore for a middleware-based approach to the construction of smart water infrastructures and investigate on the best approach for a multi-radio communication platform for reliable near-realtime message delivery. We focus more specifically on waste-water systems, and review the challenges and potential approaches available to water companies. We review one of the challenges which is how weather can negatively impact communications done on a test bed. Using this analysis we then propose a high level architecture of an integration platform for smart waste-water infrastructures.**

I. Introduction

Efficiently functioning water infrastructures are essential for modern living standards. They are well known for delivering drinking water, but they also play a key role in handling waste-water and mitigating extreme weather events such as floods and droughts. Managing, maintaining, and updating our water infrastructures is costly and complex. Water infrastructures are heavily distributed (over several 10,000 km^2 in some instances), include a wide range of equipment (pipes, pumps, sewers, vanes, treatment plants, controllers), and have often been constructed over several decades, sometimes going back as far as Victorian times.

Water companies are under increasing pressure to update and improve their infrastructure as environmental regulations are becoming more strict, water consumption surges (mainly due to population growth), extreme weather events occur more frequent and energy costs rise. One important direction of work to address these challenges is the transformation of existing water infrastructures into "smart" systems. The infrastructure is augmented with networked sensors and actuators which are used to implement fine grained automated control. It is expected that a smart water system can provide new capabilities, improve services and reduce operational costs. However, despite promising starts [1], [2], few smart water systems are in production today. One reason, we argue, is the lack of an appropriate integration platform (a "middleware") tailored towards the water industry.

Currently, it is very cumbersome to automate a new aspect of a water infrastructure. A vertical integration approach is followed where sensors, actuators, interconnecting networks and the control logic are designed and deployed for a particular automation task. Reuse of deployed equipment and software for different automation tasks is only possible with limitations. Furthermore, the design of a new automation task involves experts of all system layers.

We argue that an integration platform would simplify implementation of novel automation tasks. We envision a middleware which can provide standardised access to sensors and actuators, communication between deployment sites and defined interfaces to host control logic. Such system would i) enable experts to focus on implementation of control tasks without considering low-level communication with sensors and actuators ii) enable reuse of distributed sensors and actuators to craft new automation tasks.

In this paper, we focus specifically on the case of waste-water systems. We discuss the current needs of such systems in terms of control, distribution, and integration, based on our current work with Anglian Water Services Ltd; one of the largest water utility companies in the United Kingdom. We then review potential solutions and current approaches to these problems. We shall also demonstrrate our claim for the need to have multi radio links to support our proposed framework and finally, propose some research avenues for the development of a modular and incremental middleware for distributed waste-water control.

II. Waste-Water Infrastructures

waste-water networks are complex infrastructures that combine civil engineering works (sewers, basins, reservoirs), hydraulic actuators (pumps, gates, valves), sensors (water levels and flows, toxins, gasses), and control devices (for example, Programmable Logic Controllers). The control logic used in waste-water networks is often very simple, relying on fixed threshold values to trigger behaviours (e.g. switching a pump on or off), but more advanced control techniques are now being considered in order to improve infrastructure capabilities [2], [3].

In the following paragraphs, we describe in detail the structure and constituents of existing waste-water networks. We then provide an overview of envisioned extensions to waste-water networks which require a smart infrastructure that is currently not in existence.

A. Deployed Infrastructure

A waste-water infrastructure is usually organised in catchments. Each sewer catchment consists of a connected network of sewer pipes that collect sewage in an area and pumps it to a treatment plant or a discharge point. The number of catchments managed by a water company can be substantial and, taken together, can cover an extensive area. Anglian Water for instance collects waste-water from about 6 millions customers through 1,100 waste-water catchments over an area 27,500 km^2 in the East of England. Many catchments use a *combined sewer system* which collects both waste-water from households and water during rainfall. A combined sewer system must have enough capacity to prevent flooding in cases of heavy rainfall.

Mere gravity is usually insufficient to transport water in a sewer catchment. A catchment is therefore often equipped with a set of pumping stations that transport waste-water over an elevation, so that it can continue to flow under the effect of gravity. A pumping station is built around a wet well; an underground reservoir that acts as a buffer for incoming water (sewage and rain water in a combined system). A wet well is usually equipped with a number of pumps (duty pump, assist pump and storm pump; see [3] for more details of pumps).

The pumps of a wet well can be switched on and off, and must be controlled to process the incoming water, while minimising energy consumption, and optimising the pumps' lifetime. Currently, decisions on pump operations are made locally within one pumping station. Wet well filling levels are monitored and pumps are controlled such that energy consumption is minimised while pump lifetime is maximized [3]. The available water buffer of the wet well is used to bundle and shift times of pump activity. However, the use of the water buffer in the wet well must be managed carefully as capacity must remain to deal with heavy rainfall. The opportunities for energy savings by pump management are substantial. Anglian Water for instance spends about £60 million pounds in energy yearly, with £32 million spent on waste-water operations [3].

B. Envisioned Smart Infrastructure

The existing infrastructure does not manage available wet well capacity efficiently. Rain fall predictions are not taken into account and more importantly, the situation of interconnected pumping stations is not analysed as a whole. If it is known that rainfall probability is very low, a wet well buffer capacity may be used more aggressively to improve energy consumption of pumps. If rainfall probability is high, pumps may be activated to increase buffering capacity of the system (increasing energy costs). To implement such behaviour, the control logic would need access to external weather data which a smart infrastructure could provide.

A single pumping station may not be in danger of running out of capacity. However, we may have the situation where several pumping stations feed into another station which then runs out of capacity and flooding occurs. This can be avoided by communicating such situation to other pumping stations. In essence, the available capacity within different stations should be managed as a whole. It would be possible to use buffer capacity more efficiently which would allow us to improve energy consumption of pumps. In addition, the system would be able to control the point of flooding if capacity of the catchment as a whole is reached. A smart infrastructure interconnecting sensors and actuators in pumping stations would allow us to implement the outlined behaviour.

III. Smart Waste-Water Infrastructure

A smart waste-water infrastructure has to fulfil a set of basic requirements which are defined by business processes used in water companies and by the nature of the infrastructure itself. Next we list the main requirements and subsequently we provide a system architecture which is able to fulfil these.

A. System Requirements

Separation:: It has been realised that a smart waste-water infrastructure would benefit from a separation of control logic implementation and data acquisition. The design of control mechanisms and the installation of sensors, actuators and communication links generally falls in separate domain expertise. It is useful to define a clear interface between these groups to enable them to develop and improve their system elements independently. An additional benefit of such separation is the ability to reuse sensors, actuators and communication links for a number of control mechanisms which require these.

Decentralisation:: Due to that waste-water infrastructures span vast areas and comprise a huge number of system components, it is not desirable to use a centralised approach. It is not feasible to route all sensor information to a central point where decisions are made and send actuator commands back into the field. Instead, decision making should be carried out in a decentralised fashion.

Limited Autonomy:: Given the critical nature of waste-water systems, it is still necessary to monitor all decision making centrally. It should be known what actions decentralised decision making components are implementing. System debugging and fail safe's must exist and decision making processes must be traceable. Predefined parameters must exist for decision making algorithms so that local decisions are known to have an outcome within its predefined parameters.

Heterogeneity:: A waste-water system is built over many decades and it must be expected that a vast variety of different technologies are added over time. A variety of sensors, actuators and different types of communication links must be included. It is not feasible to assume that a large number of already deployed systems are replaced to enable a smart waste-water infrastructure. Some previous projects in middleware offer desirable properties such as genericity and transparency exist [4], [5] that shields other domain experts from low level system intricacies.

Resilience:: A waste-water system must function reliably. In particular, we expect the system to function accurately when challenged (e.g. severe flooding). However, in situations where the system is challenged and we rely most on it, we would experience as well the highest probability of sensor, actuator and especially, communication link failures. A system is required which provides sufficient resilience to ensure a smooth operation when challenged by severe meteorological phenomena.

B. System Outline

We plan to augment pumping stations with a waste-water controller (Shown in Figure 1). waste-water controllers will be able to communicate and form a distributed integration platform. Different control tasks can be deployed which make use of abstract sensor inputs and actuator outputs. Sensors and actuators may be local or available via another waste-water controller. This complexity is hidden from the control task implementation via abstraction layers. A communication layer is used to provide communication via a range of interfaces that may be available (e.g. GSM, local RF links).

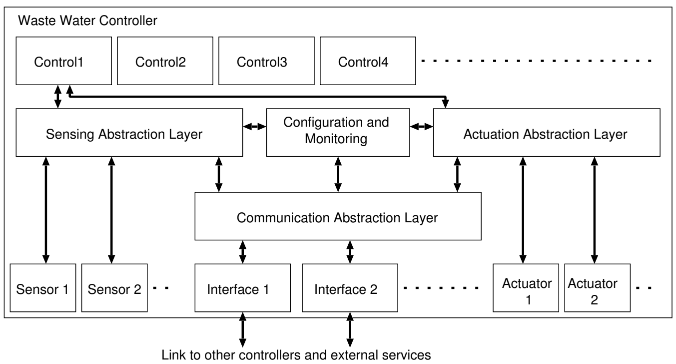

Fig. 1. Integration platform for the waste-water infrastructure

Control Tasks:: The waste-water controller will provide the ability to host generic control algorithms (e.g. Fuzzy Rule Inference systems) [6]. These may be often relatively simple but in certain situations, they may become quite complex. For example, in a simple case, a local sensor value may be compared periodically against a threshold. If the threshold is reached, an actuation command is issued (e.g. pump off or on). In a complex case, the control algorithm may use a variety of local and remote sensor inputs and issues commands to local and remote actuators. A control task will specify the nature of required inputs and outputs. In particular, frequency and reliability constraints of inputs and outputs must be described. The underlying abstraction layers will make use of this information to select communication methods and interfaces that can fulfil these requirements.

Sensing Abstraction:: Sensors may be local or accessed remotely via another waste-water controller. Sensors may use a variety of different technologies. Furthermore, a sensor may also be virtual which means that sensor data is generated by other means than a physical sensor (e.g. weather data may be provided buy virtual sensors). These differences are hidden by the sensing abstraction and control tasks can be implemented without considering the nature of sensor inputs.

Actuation Abstraction:: This abstraction is comparable to the sensing abstraction but handles outputs rather than inputs.

Communication Abstraction:: The communication abstraction provides communication capabilities to the sensing and actuation abstraction. A waste-water controller will be usually equipped with a variety of communication interfaces. For example, a GSM modem and a wireless transceiver (such as Xbee 868Mhz) providing direct links to other pumping stations may be integrated. There is also a need to monitor at which stages during a day when radio links are optimal. There is a need for this abstraction layer to determine the optimum link at a particular point in time depending on near real-time requirements to control pump activations when it is most needed such as when flooding is predicted and certain radio links fail.

Configuration and Monitoring:: This element is used for system configuration. An important aspect of the component is monitoring of the control tasks and to ensure that safe boundaries for actuation are implemented. Furthermore this component is responsible to detect and resolve control conflicts. Conflicts may occur when two control tasks aim to control the same set of actuators.

IV. Multi radio interface link quality test bed

In this section, we highlight the need for having a multi-radio interface link so that the adaptive framework can use the optimal link when weather conditions threaten communication links. The map on figure 2 shows the locations of the transcievers; to the south, an xbee node and to the north, a box carrying an xbee with a GSM modem.

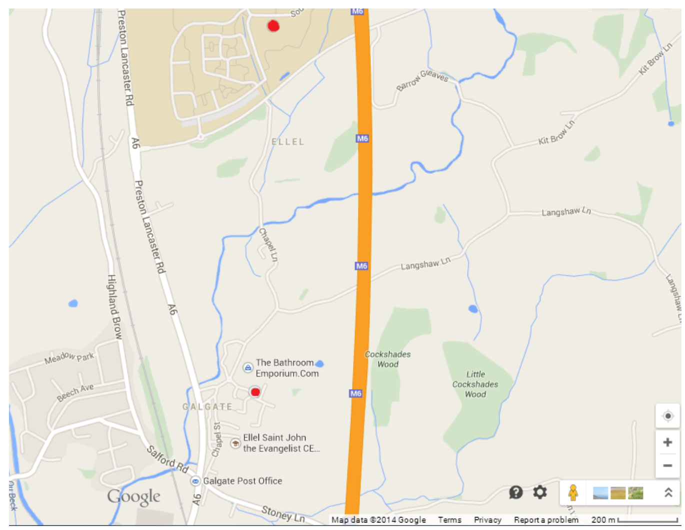

Fig. 2. Map showing locations of xbee and GSM node

A. RSSI strength and effects of meteorological conditions

During May to July 2014, we organised a test bed placed an xbee node 1 Km apart that would send a data packet. The nodes on each side would log a timestamp and the RSSI on each xbee node. One of the nodes had a GSM modem (Huawei E220) that is connected to a GSM carrier (Giff-Gaff PAYG which is operated under O2/Telefonica). A C module was coded to fetch the GSM RSSI levels which normally receives signals from the carrier every 2 seconds which updates its RSSI level. Xbee RSSI is fetched using local and remote AT commands and the RSSI level is logged together with a timestamp that collects RSSi data once every 30 seconds. We also use a weather station to collect weather data such as air pressure, temperature, relative humidity (shown by dew point and air temperature; the closer these data points are, the) and rainfall.

On the graphs, we record times from 00:00 to 23:59 within a 24 hour period and highlight cluster areas where xbee packet drops have been greater than 3 packets for every 10 packets sent (a 30 percent tolerance within a 5 minute period).

B. Graphs and Observations

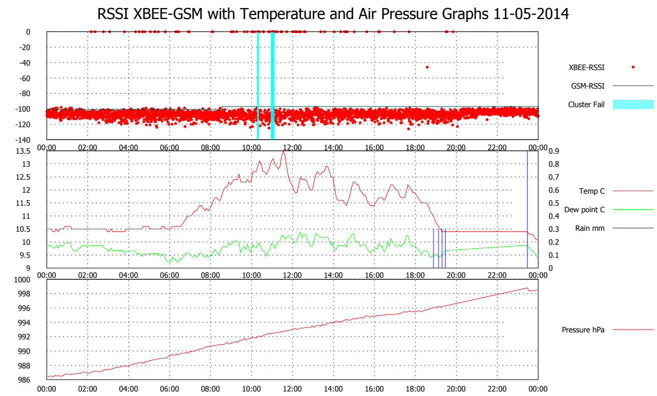

Fig. 3.

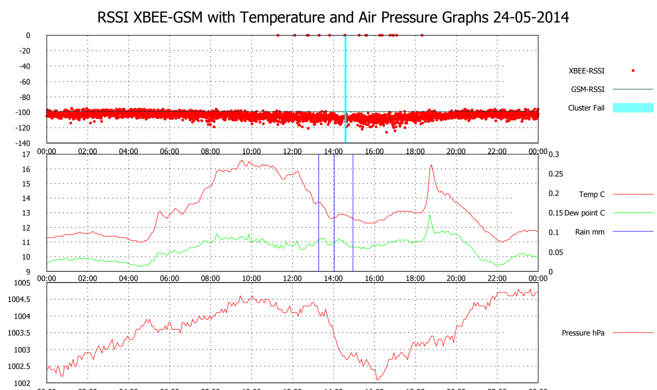

Fig. 4.

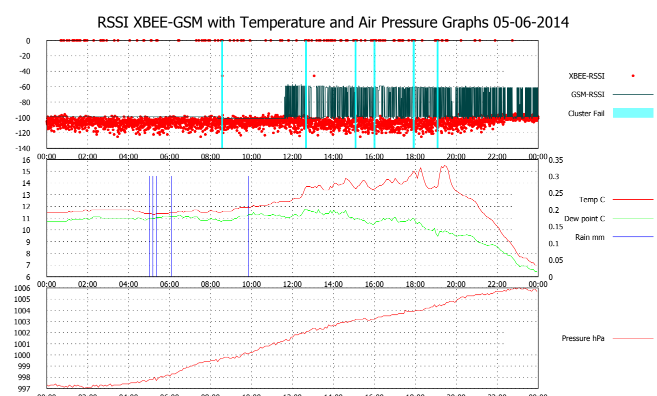

Fig. 5.

During the experiment, various challenges were faced which nullified results. Such errors such as erroneous RSSI fetched from the GSM, hardware bugs present in raspberry pi R1 with power issues, water penetration and equipment failure

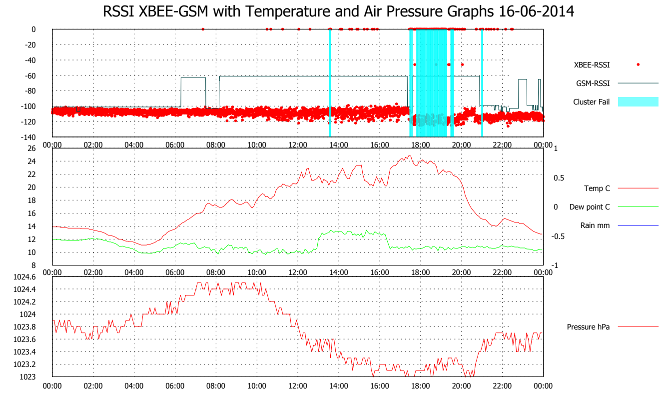

Fig. 6.

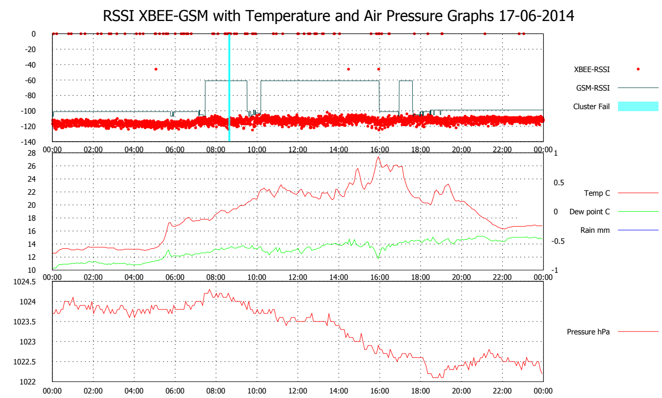

Fig. 7.

was experienced due to harsh weather conditions which slowed the experiments. We selected the best days that back up our claim were there was significant packet losses as shown in clusters and where the data was reliable to draw conclusions. We observe that there have been days (we include two days in May and three days of June 2014) where xbee RSSI worsened during the day (RSSI -100 or less) and GSM signal was acceptable between -100 and -60 which crosses the boundaries between ”Marginal”, ”Acceptable” and ”OK”. We also observe that Xbee failure tends to be most prominent during the day when air temperature peak (most notably on figure 6). We do suspect however that changes in air pressure may have a negative effect as we observe that packet failure seem to occur when there are sudden disturbances in air pressure which is an indication that there is a quick shift in air masses that flow from a region of high pressure to a region of low pressure that are either cold or warm [7]. We were not able to observe significant cluster failure when changes in air pressure were occuring, but more data is required to back this claim. We also observe that rain does not seem to affect xbee radio RSSI levels.

V. Conclusions

We have sketched an integration platform for smart wastewater infrastructures and aim to implement the outlined middleware solution and deploy a prototype within the Anglian Water infrastructure. We believe that an integration platform with the capabilities outlined in this paper is necessary to achieve the goal of a smart waste-water infrastructure. The described solution simplifies the deployment of novel control tasks, and prevents potential duplication of systems when several independent control tasks have to be deployed in a waste-water system. Our test bed also proves our claim that there is a need to support our framework with multiple radio links in order to provide resilience when weather conditions worsen and which links are required to work to send commands that operate the duty and storm pumps from the wet well.

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