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A multi-agent architecture for diagnosing simultaneous faults along water canals

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ABSTRACT

Water is intensively used in mankind activities, in particular in agriculture. Water is commonly conveyed for agriculture purposes through water canal networks which are large-scale spatially distributed systems crossing extensive regions. In the presence of leaks, unauthorized water withdrawals, water depth sensor faults or gate faults, the quality of service can be severely compromised. A system able to diagnose which type of fault is present at a given time is of vital importance to access the current state of the water canal and proceed to restore its nominal condition. This paper proposes a multi-agent architecture to simultaneously detect, isolate and estimate lateral outflows (e.g., leaks or water withdrawals) and hardware faults (e.g., a gate obstruction or a downstream water depth sensor fault) in water canal networks. First, the main canal network is broken down into several subsystems composed of a single canal pool with the corresponding gate. Then, an agent is assigned to each subsystem aiming at its fault diagnosis. The approach is based on the generation and evaluation of residuals obtained from the comparison of model-based output signals with real data. Application to an experimental water canal bears out the proposed architecture as a valuable tool for monitoring and supervising general water canals.

1. Introduction

Water is an essential resource for all life species, in particular human life. Water is used in a wide range of applications, from agricultural to industrial applications, domestic use and recreation. Unfortunately, water is becoming a rare resource so engineering contributions to increase water use efficiency are welcome. It is well known that agriculture consumes around 70% of the total world fresh water resources (Mareels et al., 2005). Water for agriculture is usually conveyed through water canal networks which are typically conceived as large-scale spatially distributed systems. Water canal networks can suffer unpredicted disturbances and faults which may compromise the quality of service. In order to keep the quality of service at acceptable levels it is important to have a reliable system able to detect which type of fault is affecting the system whenever it occurs.

A system which is able to detect, isolate and identify a fault is nominated as a Fault Diagnosis and Isolation (FDI) system (Chen & Patton, 1999). Different FDI design approaches can be found in the literature. Early works from Beard (1971) present a FDI system based on a failure detection filter which could be applied to linear systems. Recent results from Arogeti, Wang, Low, and Yu (2012) suggest a single monitoring framework to deal with sensor faults. A state-of-the-art review of methods and applications for data-driven fault detection and diagnosis developed over the last two decades can be found in Qin (2012). The increasing complexity of processes to which FDI is being currently applied has triggered the use of decomposed approaches. For instance, Liu, Chai, and Qin (2012) propose a decomposition of the main large-scale problem (continuous annealing process line) into multiple subsystems to reduce the ambiguity of fault diagnosis.

Regulation of water depths in canal pools based on feedback controllers can lead to improvements in water spillage (Litrico, Fromion, Baume, Arranja, & Rijo, 2005; Malaterre & Baume, 1998; Schuurmanns, Hof, Dijkstra, Bosgra, & Brouwer, 1999; Weyer, 2008). Three different types of faults are commonly encountered in water canal networks (Bedjaoui, Litrico, Koenig, & Malaterre, 2006): (1) lateral outflows, (2) actuator faults and (3) water depth sensor faults. Locally the impact of a water depth sensor fault or an actuator fault can be the same as of a lateral outflow. Although feedback controllers may accommodate gate faults, they are not designed for this purpose. For instance, whenever a gate fault is accommodated, the system shifts from its nominal operating

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condition possibly leading to unwanted interactions with neighboring water structures. In case of a water depth sensor fault the water canal network will no longer deliver the agreed volume of water to the client and service can be compromised, with possible impact on system integrity.

Fault diagnosis in water canal networks is a current active research field. In Bedjaoui et al. (2006) a fault detection and isolation scheme based on a bank of observers is proposed to detect and isolate non-simultaneous faults. Unmeasured outflows are distinguished from other faults in Bedjaoui, Litrico, Koenig, Ribot-Bruno, and Malaterre (2008) using data reconciliation based on Kalman filtering, but additional measurements for the flow velocity are required. The leak detection presented in Weyer and Bastin (2008) is based on a volume mass model and generates a residual representing the mismatch between the model and the observed data although no considerations about other faults are considered. In Bedjaoui, Weyer, and Bastin (2009) a Luenberger type observer based on Saint-Venant equations is used to estimate the size of a water leak. In Bedjaoui and Weyer (2011) a comparison between different approaches for leak detection, estimation, isolation and localization is presented, having as limitation the assumption that only a single sensor fault and leak may occur. Based on residual generation and evaluation, Nabais, Mendonça, and Botto (2012a) proposed a fault isolation architecture for typical faults in irrigation canals. The present work makes a direct contribution on fault diagnosis along water canal by considering explicitly lateral outflows, gate faults and water depth sensor faults.

In this paper an innovative multi-agent architecture for simultaneous diagnosis of lateral outflows, gate faults and sensor faults for water canal networks is proposed. The approach is based on measurements from water depth sensors which are usually available at these infrastructures. The framework is able to isolate and estimate different faults that occur along a water canal, a distinctive feature when compared with other methods presented in the literature. The proposed solution starts by dividing the canal network into a set of subsystems (composed of a pool and the corresponding downstream gate) to which an agent is assigned to execute the subsystem fault diagnosis. Through this distributed approach, the communication of a large amount of data into a single decision center to execute the system fault diagnosis is avoided. Information exchange is thus limited to neighboring agents leading to a reduction of communications in the overall system. This multi-agent approach features a modular and scalable design architecture easing the addition of more subsystems (new agents running the diagnosis algorithms). The proposed multi-agent architecture has the following distinctive characteristics:

- it allows for detection and isolation of lateral outflows, gate and water depth sensor faults present at the same time along a water canal;
- the water depth sensor faults can be isolated requiring a minimum configuration of three sensors along a canal pool, and for some existing canal pools at the cost of one extra water depth sensor;
- it is easily applied to existent water canal networks, since it relies on flows and water depths estimations which can be provided by first principle or data driven models;
- it has a modular feature, since each agent is responsible for the fault diagnosis at a given pool;
- it is easily scalable to large-scale canal networks since an agent is assigned to run the diagnosis algorithms with limited communications to the upstream and downstream neighbors.

The paper is divided into the following sections. In Section 2 typical faults for water canal networks are presented and grouped into different categories based on their impact in the system behavior. The multi-agent fault diagnosis architecture is presented in Section 3 and its structure composed of two algorithms is fully described, namely the Distributed Fault Isolation and the Sensor Fault Isolation algorithms. The performance of the proposed approach is analyzed in Section 4 using real data extracted from an experimental water canal located at the University of Évora, in Portugal. Finally, Section 5 presents final comments and future research directions.

2. Faults in water canal networks

Water canal networks are usually set to work with desired water depths at specific locations which are controlled using hydraulic structures such as gates (Weyer, 2008). The following faults can be typically found in water canal networks (Bedjaoui et al., 2006),

- *Lateral outflow fault*: This type of fault accounts for client offtakes, unauthorized water withdrawals and existing leaks in the canal structure that may occur along the pool, not necessarily confined to the pool downstream location. A typical example is a water withdrawal to a lateral canal.
- *Gate fault*: This fault accounts for either a gate obstruction, by sediments or external objects, or a gate not being properly sealed. These faults can be modeled as a bias in the gate elevation and have a direct effect on gate flow estimation. If the gate is partially obstructed the feedback controller correctly decides to open the gate and the desired water depth can still be guaranteed, the fault has been accommodated. In case of an obstruction, the gate fault is equivalent to a bottleneck and compromises high flows if required. As modern gates have their own built-in systems for fault diagnosis, faults related to the gate equipment (as the gate elevation sensor) are not considered explicitly.
- *Water depth sensor fault*: Depending on the sensor location this type of fault has different impacts on the system behavior. When the sensor is used exclusively for monitoring issues the impact is reduced but if the sensor is used for feedback the impact can be critical. Without additional indication the feedback controller will be deceived and will follow the erroneous information, compromising the quality of service and security (for instance, overtopping phenomena may occur).

Typical faults in water canal networks can be categorized into classes based on their nature and impact on the estimated canal pool behavior. In this work faults are categorized into three major groups (see Fig. 1): *lateral outflow faults* F_O, *hardware faults* F_H and *water depth sensor faults* F_S.

Hardware faults compromise the gate flow estimation can be either a gate fault F_{H_g} or a fault located at a water depth sensor, named a hardware sensor fault F_{H_s}. These two faults have a similar impact locally as they are responsible for an erroneous gate flow

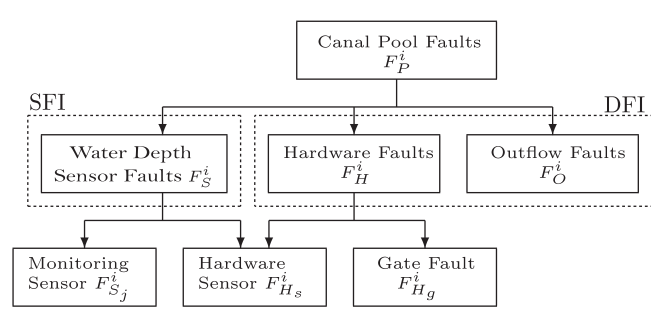

Fig. 1. Fault classes at canal pool *i*.