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SENSOR FAULT TOLERANT ARCHITECTURE FOR IRRIGATION CANALS

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Abstract: Irrigation and drainage canals are some examples of water conveyance systems spread worldwide. These systems are characterized for the transport phenomena and are usually operated under closed loop control. Typical considered faults are the unmeasured water extraction, gate and sensor fault. The classical controller is projected to reject the unmeasured offtakes and can also accommodate the gate fault. The sensor fault is a critical fault as it deceives the controller. As the service is based on water levels a falsified information compromises service quality. Depending on fault intensity, security issues may arise. Here we propose a sensor fault tolerant architecture to the downstream water level sensor fault. This architecture is based on two components, first the fault is detected and isolated then the estimation intensity is used to correct the nominal reference. Based on updating the reference water depth, additional information is passed to the operating controller for sensor fault accommodation. The architecture is independent from the controller design and therefore can be integrated in old irrigation canals.

Keywords: Sensor fault, Fault tolerant control, Fault detection and isolation, Irrigation.

1. INTRODUCTION

Water is a vital resource for life on earth. Mankind way of life is based on water consumption: industry, agricultural and domestic activities. Now is time to use this resource with extreme efficiency to not compromise the future. Agricultural has a great impact in water consumption and in respect to Portugal 81.8% of the available water is used for irrigation (Raposo, 1996). As water is not always available near the consumers it is conveyed by a network of canals. The objective of these facilities is to make water available to farmers while minimizing losses. The canal losses can be caused by bad networks management due to oversupply which can cause spillage along the canal and outflows at the end of the networks system. As the canal network in most cases is a civil engineering structure with many years, water losses due to leaks are often expected. Having a system able to detect structure faults and supporting the management system is an important contribution for water saving.

A system that includes the capacity of detecting, isolating and identifying faults is called a fault detec-

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tion and isolation system (Chen and Patton, 1999). Many research has been carried out using analytical approaches and model-based approaches to tackle this problem. The use of Fault Detection and Isolation (FDI) in Fault Tolerant Control (FTC) is very important in the active way of achieving fault-tolerance, by detect and isolate the faults. After the fault indication by FDI, the system can then be reconfigured or restructured. The fault diagnosis in water conveyance systems has been addressed in (Bedjaoui *et al.*, 2006; Bedjaoui *et al.*, 2008; Weyer and Bastin, 2008). A comparison between different methodologies for leak detection is presented in (Bedjaoui and Weyer, 2011). Fault tolerant control in irrigation canals has been tackled by (Choy and Weyer, 2008) in an approach based on observers and reconfiguration control to mitigate the fault presence.

The sensor fault tolerant architecture proposed in this paper is based on two tasks: fault diagnosis and reference update. The fault diagnosis is used to obtain information about the fault. At the cost of at least 3 water level sensors by pool the downstream water level sensor fault is correctly isolated and estimated. As the canal pools are usually equipped with water level sensor upstream and downstream in each gate there are already two water level sensors available by pool. The additional cost is only one water level sensor by pool. Based on fault estimation the nominal reference can be updated to neutralize the sensor fault and restore the service quality. The architecture is independent from the operating controller allowing implementation in common irrigation canals.

In section 2 the fault problematic for water irrigation canals is discussed. Then the algorithm for fault diagnosis is presented. Finally the fault tolerant control feature is added. The performance of this method is studied in 3 for single and multiple faults and in particular is shown how the system performance is affected by the downstream sensor fault. In section 4 final comments and future directions are pointed.

2. FAULT TOLERANT ARCHITECTURE

2.1 *Problem description*

The flow in water canals is well described by the Saint-Venant equations, a pair of quasi-linear partial differential equations of hyperbolic type (Akan, 2006),

$$\frac{\partial Q(x,t)}{\partial x} + B(x,t)\frac{\partial Y(x,t)}{\partial t} = 0 \qquad (1)$$

$$\frac{\partial Q(x,t)}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2(x,t)}{A(x,t)}\right) + \dots$$

$$\dots + g \cdot A(x,t) \cdot (J(x,t) - I(x)) = 0 \qquad (2)$$

where $Q(x,t)$ is the flow, $Y(x,t)$ the water surface depth, $B(x,t)$ the water surface width, $A(x,t)$ the water cross-section area, g the gravity acceleration, x the longitudinal abscissa in the flow direction, t the time instant, $I(x)$ the bottom slope and $J(x,t)$ the energy gradient slope. These equations are non-linear with unknown analytical solution. In a steady configuration, with no time derivatives, the Saint Venant equations becomes (Litrico and Fromion, 2009),

$$\begin{aligned} \frac{dQ(x)}{dx} &= 0 \\ \frac{dY(x)}{dx} &= \frac{I(x) - J(x)}{1 - F^2(x)} \end{aligned} \qquad (3)$$

where F is the Froude number $F = \frac{V}{C}$ with $C = \sqrt{g\frac{A}{T}}$ and T is the top width. The ordinary differential equation (3) allows, for a nominal flow, the backwater determination $Y(x)$ as long a boundary condition for the downstream water depth is given.

2.2 *Faults definition*

Typically in water conveyance systems the existent faults are commonly classified into one of three categories: unmeasured flow withdrawal, actuator fault or sensor fault. For a given pool these faults can produce a similar effect and therefore is not uncommon to treat all of them as an unmeasured flow withdrawal. The gate fault and sensor fault can be classified as hardware faults since they do not involve any flow exchange with the surroundings. In Fig. 1 the fault hierarchical relation considered for irrigation canals is presented. Depending on the pool equipment we may have several water level sensors along the canal axis Fig. 2. The critical fault is located on the sensor responsible for reading the controlled variable, usually

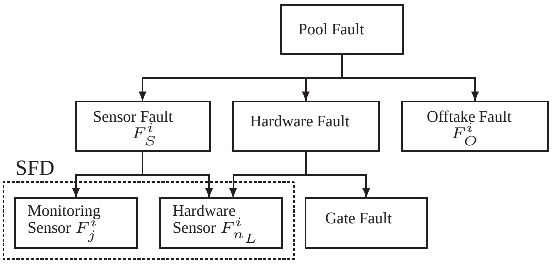


Fig. 1. Type of faults for an irrigation canal pool i.

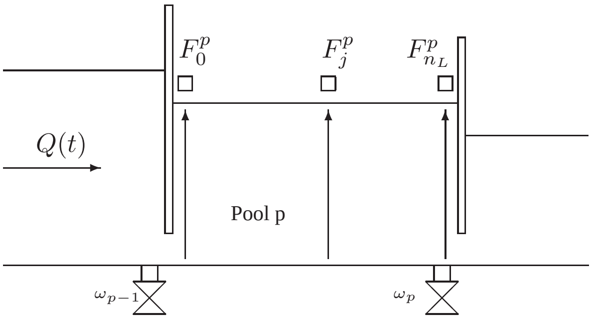


Fig. 2. Fault location for a generic pool i.

the downstream water depth. The other sensor faults are neutral to the system performance as they are used for monitoring issues. The downstream water depth information is essential for the operating controller. If a fault exits on the sensor it will deceive the controller that will try to follow the erroneous information. The consequence is that the desired water depth is compromised as well as the service quality offered to the clients. If the fault intensity is negative, the sensor indicates a lower value for the water depth, the controller will raise the water depth and depending on the fault intensity flood is a possibility.

2.3 *Sensor Fault Diagnosis (SFD)*

A sensor fault can be easily detected by comparing the water depth sensor data with the backwater for steady state. An important issue here will be the controller performance, in particular its ability to produce a smooth response without consecutive wave formation or oscillations. Some compromise between time detection and false detection has to be considered as the canal is subjected to disturbances. The estimation of the pool backwater can only be done with the available information about the pool state; downstream water depth given by the sensor $\bar{Y}_L(k)$ and the downstream gate flow estimation $\widehat{Q}(k)$.

The gates existing in irrigation canals can be classified as overshot gates, with the flow over the gate, or undershoot gates, with the flow under the gate. Considering free flow conditions for the first type and submerged flow conditions for the last one the gate equations (Chaudry, 2008) can be used for flow gate estimation $\widehat{Q}(k)$.

At a first stage we assume the information collected from the canal is totally correct. The backwater is estimated using the available information $(\widehat{Q}(k), \bar{Y}_L(k))$ as a steady state for (3). Consider a generic pool p with j water level sensors where $j = 0$ means the upstream location while $j = n_L$ means the downstream location Fig. 2. Once the pool backwater $\hat{Y}_j(k)$ is estimated a residue $r_j(k)$ between the sensor value and the estimation $\widehat{Y}_j(k)$ can be calculated for time instant k, for all locations except $j = n_L$,

$$r_j(k) = \bar{Y}_j(k) - \widehat{Y}_j(k) \tag{4}$$

The sensor alarm f_j will be triggered if a certain threshold δ_y is violated,

$$\begin{cases} |r_j(k)| \geq \delta_y & \Rightarrow \quad f_j = 1 \\ |r_j(k)| < \delta_y & \Rightarrow \quad f_j = 0 \end{cases} \tag{5}$$

This procedure is straightforward for all sensors except for the downstream sensor. A good way to account for the pool water depth status is to compute the sum of all triggered alarms,

$$\Upsilon(k) = \sum_{j=0}^{n_L-1} f_j(k) \tag{6}$$

Some different scenarios may occur: $\Upsilon(k) = 0$ meaning that there are no sensor alarms; $\Upsilon(k) = 1$ there is only one sensor alarm and its location is given by the corresponding triggered alarm f_j; $\Upsilon(k) = n_L - 1$ means that all water level sensor are triggered. In this extreme configuration the most likely situation is that the information used for backwater estimation was not consistent with the real system $(Q(t), Y_L(t))$, which is equivalent to say that the fault is located at downstream. Alarms f_j from $j = 0 \ldots n_L - 1$ are reset to zero and f_{n_L} is set to one. To robustify the isolation some additional tests may be included. The alarm f_{n_L} is only triggered if,

$$\left| \frac{\sum_{p=0}^{n_L-1} r_p(k)}{n_L} - r_j(k) \right| < \delta_y \tag{7}$$

is verified for $j = 0 \ldots n_L - 1$. This is equivalent to say that all sensor errors must be inside a bound. To reduce the impact of water level disturbances introduced by the operational controller a moving window can be used to evaluate the ratio between the number of triggered alarms inside the window and the window size. The window dimension τ_a should be related to the transport pool delay.

Once the downstream water level sensor is isolated the next stage is to estimate the fault intensity. For the monitoring sensors the fault intensity is given by the corresponding residue $r_j(k)$. For the downstream sensor the procedure is more complex. As the algorithm will be running for all sample times is important to have a close initial guess. The fault intensity is closely related to the residue average $\gamma(k)$. The expected true value for the water level is initially given by $\hat{Y}_L = \bar{Y}_L(k) + \gamma(k)$. The search interval is defined as $\Gamma = [\bar{Y}_L(k); \bar{Y}_L(K) + 2\gamma(k)]$. The estimated fault intensity F_γ is,

$$F_\gamma = \arg_{\hat{Y}_L} \min \sum_{j=0}^{n_L-1} \left| \bar{Y}_j(k) - \hat{Y}_j(k) \right| - \bar{Y}_L(k) \tag{8}$$

and $\hat{Y}_j(k)$ have to be in accordance with equation (3).

2.4 *Fault Tolerant Controller*

The fault tolerant controller is achieved by updating the nominal system reference R_0 by the downstream sensor fault estimation F_γ. The new reference responsible for tolerant fault control is given by,

$$R_f = R_0 + G_f(s) F_\gamma \tag{9}$$

In order to guarantee robustness the update component is filtered by a first order low pass filter $G_f(s)$ with time constant τ_f to avoid exciting the canal first oscillating mode. The fault tolerant architecture proposed is schematically indicated in Fig. 3.

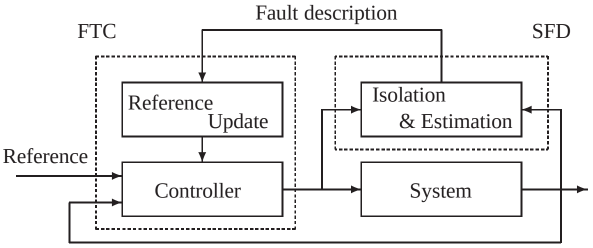


Fig. 3. Fault tolerant architecture.

3. SIMULATION RESULTS

3.1 *Irrigation Canal Description*

The algorithm performance analysis is done using the simulator (Nabais *et al.*, 2011) developed for the experimental water delivery canal hold by the NuHCC – Hydraulics and Canal Control Center from the Évora University in Portugal Fig. 4. The experimental canal has a well known geometry: the pools have a trapezoidal section with a bottom width of 0.15m, $1 : 0.15$ side slope and a maximum height of 0.9m. The canal inflow is dictated by an electrical MONOVAR valve, along the canal the water translation is assured by a bed slope of 0.0015 and the facility is designed to a maximum flow of $0.090\text{m}^3/s$. The canal ends with an overshot gate. In each pool there are water level sensors of float and counter-weight type for canal monitoring. The sensors are located at the upstream, center and downstream end. The water extraction is done upstream each gate by the existence of an offtake equipped with a flow meter and an electrical butterfly to allow water extraction. The system is considered in steady state with a nominal flow $Q_{up} = 0.040m^3/s$ and gates elevation $\mathbf{U} = \begin{bmatrix} u_1 & u_2 & u_3 & u_4 \end{bmatrix} = \begin{bmatrix} 0.25 & 0.25 & 0.25 & 0.4 \end{bmatrix} m$.

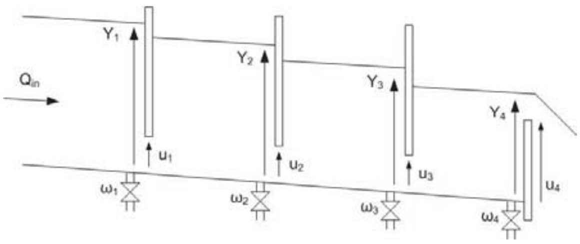


Fig. 4. Irrigation canal configuration.

3.2 *Fault Description*

The irrigation canal is considered to be under closed loop control with local upstream PI controllers (Litrico *et al.*, 2003). In terms of time–dependency we consider intermittent faults (Isermann, 2011) Fig.5. Consider the following fault definition for pool p,

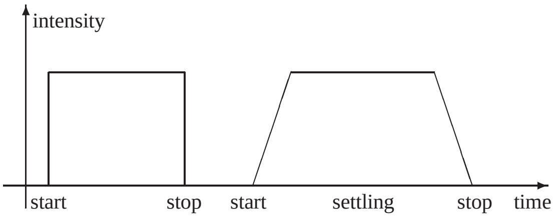


Fig. 5. Intermittent faults schematics.

- F_U^p upstream water depth sensor fault
- F_C^p center water depth sensor fault
- F_D^p downstream water depth sensor fault

For each definition an abrupt F^a and incipient F^i fault are considered. The sensor fault tolerant architecture is always running and configured with a constant threshold $\delta_y = 0.008$m, equal to the water depth sensor calibration error for the experimental canal, a moving window of $\tau_a = 17.5$s, 60% of triggered alarms inside the window and $\tau_f = 40$s. The water depth sensor fault intensity was settled to $2\delta_y$.

3.3 *Sensor Faults Diagnosis in One Pool*

The single faults specifications, start and stop time instants and intensity, are indicated in Table 1. The faults will be introduced at pool 3.

Table 1. Single faults specifications.

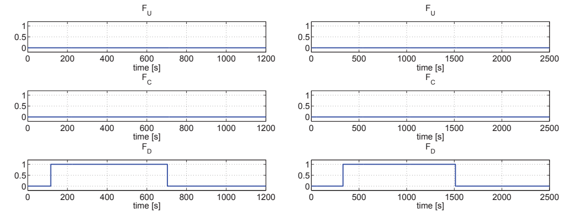
Faults	Start	Max Value	Stop	Intensity
F_U^{3a}	100s	$[100; 700]$s	700s	$+0.016$m
F_C^{3a}	100s	$[100; 700]$s	700s	$+0.016$m
F_D^{3a}	100s	$[100; 700]$s	700s	$+0.016$m
F_U^{3i}	150s	$[450; 1050]$s	1350s	$+0.016$m
F_C^{3i}	150s	$[450; 1050]$s	1350s	$+0.016$m
F_D^{3i}	150s	$[450; 1050]$s	1350s	$+0.016$m

The SFD performance is indicated in Table 2. Fault isolation time instants are conditioned to the window size τ_a considered for false alarm robustness. In Fig. 6–7 the fault isolation and estimation for abrupt and incipient faults is done accurately for the downstream sensor.

Table 2. SFD performance for single faults.

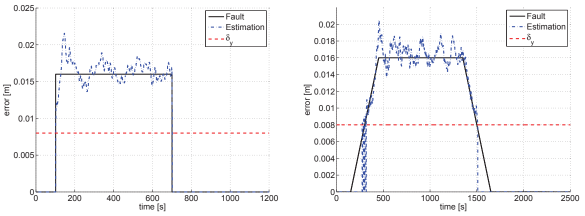
Faults	Start	Isolated	Stop	Isolated
F_U^{3a}	100s	117s	700s	703s
F_C^{3a}	100s	117s	700s	703s
F_D^{3a}	100s	117s	700s	703s
F_U^{3i}	150s	248s	1350s	1270s
F_C^{3i}	150s	319s	1350s	1199s
F_D^{3i}	150s	323s	1350s	1174s

The downstream water level sensor fault estimation is particular important for the fault tolerant controller architecture as it is the basic information to proceed with reference update. In Fig. 7 the fault estimation for the downstream sensor fault is closely to the real fault present in the system.



(a) Fault isolation for F_D^{3a}. (b) Fault isolation for F_D^{3i}.

Fig. 6. Downstream single fault isolation.

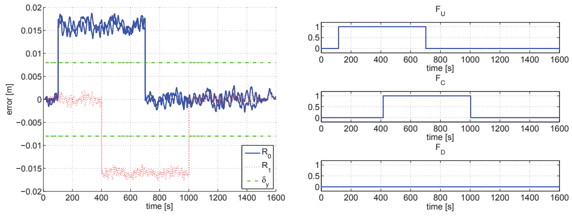


(a) Fault estimation for F_D^{3a}. (b) Fault estimation for F_D^{3i}.

Fig. 7. Downstream single fault estimation.

3.4 *Multiple Sensor Fault Diagnosis in One Pool*

It is important to see how fault detection and isolation is performing when multiple sensor faults are present in the system. Naturally, if the upstream and center water depth sensors are facing a fault of the same intensity and signal the algorithm fails as it will indicate a downstream sensor fault. This is a highly unlikely situation. The algorithm can deal with multiple sensor faults as shown in Fig. 8. The upstream and center sensor are in the interval $[400; 700]$s simultaneous in a fault mode with the same intensity but different signs.



(a) Sensor fault estimation. (b) Fault logic.

Fig. 8. Upstream and center sensor fault.

3.5 *Multiple Faults Diagnosis*

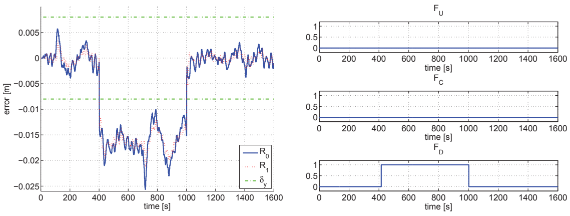
On service canals are subjected to water extractions imposed by users. The nominal controller while trying to restore the water depth will introduce oscillations into the canal that will propagate. This way is important to know how the SFD algorithm behaves in normal operating conditions. A water extraction at pool p is represented by F_O^p. Three different scenarios were tested using abrupt faults,

- Test A: downstream water depth sensor faults at pool 2 and 3 respectively F_D^2 and F_D^3;
- Test B: an offtake fault at pool 2 F_O^2 and a downstream water depth sensor fault at pool 3 F_D^3;
- Test C: an offtake fault and downstream water depth fault at pool 3 respectively F_O^3 and F_D^3.

The faults specifications and the SFD performance are given in Table 3 and in Fig. 9–10. In Test A, Fig. 9, the fault tolerant architecture is able to detect and estimate correctly the sensor fault with no interference during transients. There is no significant impact of the upstream pool behavior on the fault isolation for pool 3. For Test C, Fig. 10, the algorithm is not deceived by the existing water extraction at the same location as the sensor fault and correctly isolates the sensor fault. In Tests B and C the water extraction causes impact in fault diagnosis only during transients being more severe for test C as faults have the same location.

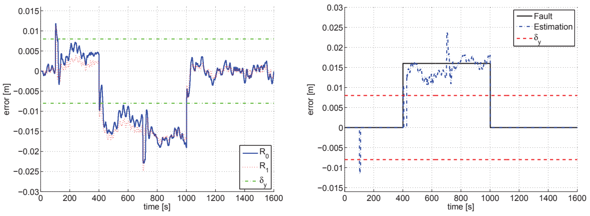
Table 3. SFD architecture performance for multiple faults.

Faults	Start	Isolated	Stop	Isolated
F_D^2	100s	117s	700s	703s
F_D^3	400s	417s	1000s	1003s
F_O^2	100s	–	700s	–
F_D^3	400s	417s	1000s	1004s
F_O^3	100s	–	700s	–
F_D^3	400s	442s	1000s	1003s



(a) Pool residues r_j. (b) Fault logic.

Fig. 9. Fault diagnosis for scenario A.



(a) Pool residues r_j. (b) Downstream fault estimation.

Fig. 10. Fault estimation for scenario C.

3.6 *Fault Tolerant Architecture Performance*

In the previous subsections the fault tolerant architecture was always active and therefore the performance increase introduced may pass unnotice. To show the impact in service quality we defined a test were the downstream fault at pool 3 starts at time instant $t = 100$s and stops at time instant $t = 1300$s. The fault intensity remains $2\delta_y = 0.016$m. Initially the fault tolerant architecture is inactive to show how the non-tolerant architecture compromises the system service quality when falsified information is provided Fig. 11. At $t = 700$s the sensor fault tolerant architecture is

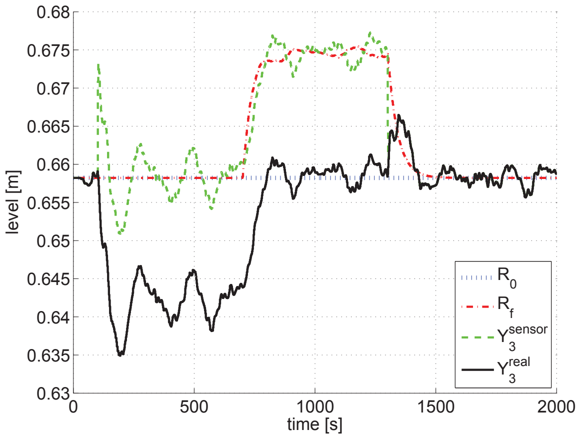
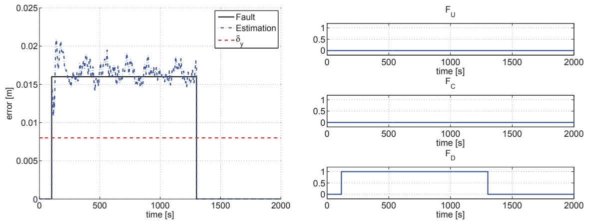


Fig. 11. System performance under FTC and non-FTC architectures.

Table 4. Performance criteria comparison between FTC and non-FTC architectures.

	MSE	MAE
FTC	0.1×10^{-4}	0.0042
non-FTC	2.6×10^{-4}	0.0162

activated and the quality of service is restored. Although the fault tolerant architecture is inactive until $t = 700$s the SFD framework is always running and the fault is well isolated and estimated from $t = 100$s to $t = 1300s$ Fig. 12. In Table 4 the error criteria Mean Square Error (MSE) and Mean Absolute Error (MAE) are presented for both architectures. The short time test executed nevertheless shows a reduction to 25% in the MAE for the FTC proposed architecture. It is important to note that the error criteria is evaluated in different conditions and time instants. The non tolerant architecture starts with nominal conditions and is unable to deal with the sensor fault. The fault tolerant architecture begins with a more demanding situation as there is a deviation from the nominal conditions and is able to restore the service quality.



(a) Downstream fault estimation.

(b) Fault logic.

Fig. 12. Fault estimation and pool status under FTC and non-FTC architectures.

4. CONCLUSIONS AND FUTURE WORK

This paper presented a sensor fault tolerant architecture that allows for downstream sensor fault tolerant control with a minimum requirement of three level sensors available on each canal pool. This is a small investment for water irrigation management compared to the resulting benefits. The work presented will be used together with fault detection and isolation for offtake and hardware faults developed by the authors to produce a detailed fault diagnosis for canal pools. In particular, different combinations of multiple faults were considered, corresponding to demanding situations where multiple effects can have similar impacts difficult to isolate. The proposed architecture will be tested in a real scenario, in particular in the experimental canal own by the NuHCC.

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