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REAL-TIME MEASUREMENT FAULT DETECTION AND REMOTE-CONTROL IN A MOUNTAIN WATER SUPPLY SYSTEM

***Sofia Fellini*[1], *Riccardo Vesipa*[1*] , *Fulvio Boano*[1] & *Luca Ridolfi*[1]**

(1) Dept. of Environment, Land and Infrastructure Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Turin, Italy.

**email:* riccardo.vesipa@polito.it

KEY POINTS

- *An algorithm for the assessment of the automated control operations of a modern water supply system is presented.*
- *The algorithm isolates faults on sensors through redundancy and residual analysis.*
- *The algorithm performs real-time selection of the most reliable measurements for automated control.*
- *A coupled model of the hydraulic and supervisory control system is used to test the algorithm effectiveness.*

1 INTRODUCTION

In mountain regions water resources are commonly available and water supply (WS) to the local communities is usually provided by municipal WS networks, which operate independently from each other.

In the event of unexpected breakdowns or droughts, this fragmentation results in inefficiencies and water crisis. In order to increase the resilience of the WS service, a growing trend is the creation of intermunicipal water networks that connect multiple local water systems (*Massarutto,* 2000).

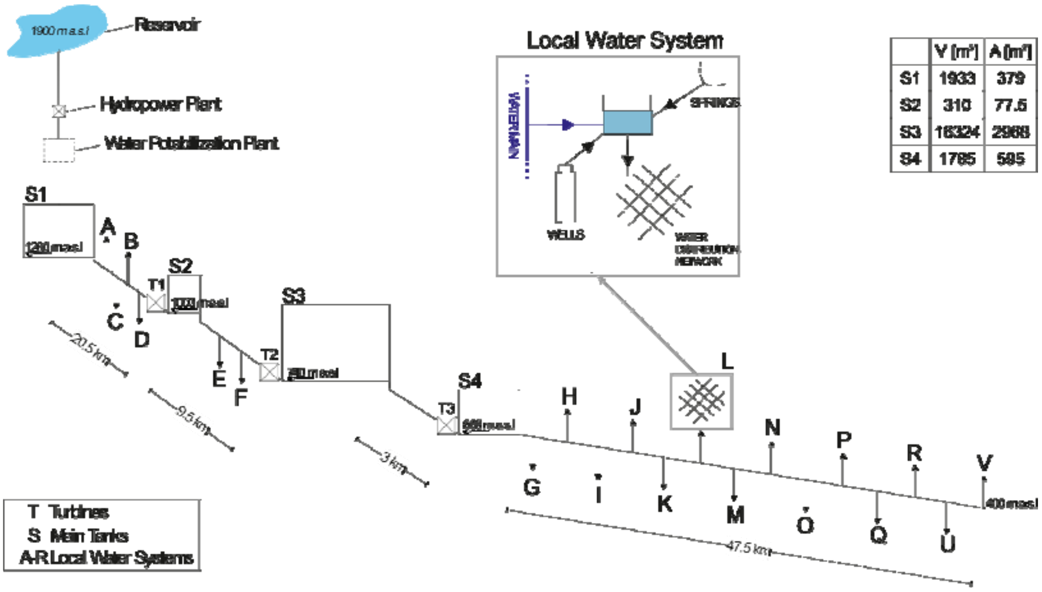
This strategy was used in an Alpine valley in north-western Italy, where an 80-km-long water main was designed to connect 20 municipal WS networks (Figure 1). The water main takes water from a high-altitude reservoir, connects the local tanks and provides additional water when needed. Moreover, there are four inline tanks along the water main, and the excess water pressure is converted into hydropower by three turbines.

The operations of this modern water supply system (WSS) require a comprehensive and automated regulation provided by a supervisory control system (SCS). Thus, flow adjustments through turbines and valves are remotely controlled according to predefined management rules and to flow and level data measured in real-time throughout the WSS (*Fellini et al.*, 2018).

Lack of data or errors in the sensors may result in a misleading regulation and in malfunctions in the WSS operations. Therefore, it is important to equip the control systems with procedures that can detect errors in sensors.

In order to increase the safety and the reliability of the system, an algorithm for the real-time detection of measurement faults has been developed. By a residual analysis, redundant measurements are compared and faults are automatically detected. Moreover, in case of errors, interruptions of the WSS operations are not accepted. Therefore, the developed algorithm guarantees the selection of an alternative correct measurement to be used in the SCS.

Hardware and analytical redundancy is largely adopted in industrial plants (e.g., *Gertler,* 1988) and in the automotive and aerospace engineering (*Chen & Patton*, 2012). However, few applications have been done for the validation of measurements in water networks (e.g., *Ragot & Maquin,* 2006). In this work an algorithm is presented for fault detection and real-time measurement validation in the SCS of this modern WSS.



	V [m³]	A [m²]
S1	1933	379
S2	310	77.5
S3	16324	2968
S4	1785	595

Figure 1: Scheme of the WSS. The capital letters (A, B,…, V) indicate the local water networks; the inset shows a typical local water system with a storage tank supplied by mountain springs, local wells, and the new water main.

2 METHODS

A simulation model was developed to analyse the performances of the WSS in different scenarios. This model consists of a coupled hydraulic model and decision model. The first one is a system of non-linear equations describing (i) the flow-head loss relation in pipes, at valves and at turbines, (ii) the flow continuity at nodes and (iii) the boundary conditions at tanks. Time evolution of the system is modelled by a succession of steady states with duration Δt. At each time step, flow in the pipes and pressure at the nodes of the WSS are computed. Moreover, the water level in the tanks is updated using a mass balance equation.

The second model simulates the supervisory control system (SCS). Management rules are implemented as algorithms in the SCADA system and were developed to optimize water supply, hydropower generation and energy saving in the whole valley (*Fellini et al.*, 2018). These rules control the operations of turbines and valves in accordance with level and flow rate data measured throughout the WSS. To guarantee the validity of these measurements, real-time fault detection in sensors is performed using the redundancy concept. This method can be applied when several values of the same physical variable are available. These values are provided by redundant gauges or by analytical models. For example, in the studied WSS two level sensors are provided for each tank (measurements A and B in Figure 2). Moreover, the tank level can be evaluated with a mass balance equation involving inflow and outflow measurements (measurement C in Figure 2). Residuals R_1, R_2 and R_3 are generated by calculating the difference between measurements two by two. Each residual is then compared to its tolerance interval. The tolerance thresholds are determined in order to include random errors related to the instrumental precision. If the two residuals calculated from a measurement are both out of tolerance, then the gauge providing that measurement is identified as faulty (for example if R_1 and R_3 are out of tolerance, the level sensor A is identified as faulty).

Besides real-time error detection, the developed algorithm selects the most accurate data to be used in the control system. For each measurement tern, the minimum residual is identified (M in Figure 2). The two measurements involved in the calculation of M are considered valid and one of them is used for the control operations. This last choice is based on technical considerations. Generally, priority is given to direct measures compared to indirect ones (i.e., measures from analytical models).

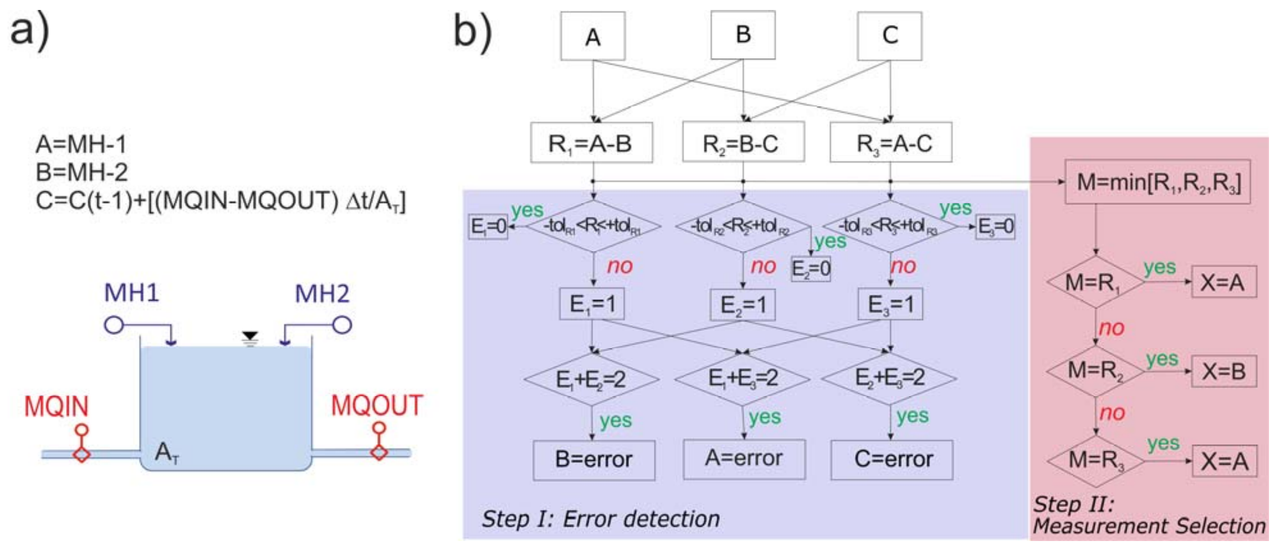


Figure 2: a) Level (MH-1 and MH-2) and flow rate (MQ-IN and MQ-OUT) sensors installed in a tank (with area A_T) of the WSS. The system of equations provides three redundant values of the tank level. b) Algorithm for fault detection in the WSS gauges and for the choice of the most reliable measurement to be used in the control operations.

3 RESULTS AND DISCUSSION

The above presented algorithm for real-time fault detection and measurement selection was applied to each measurement involved in the control operations of the SCS. First, the available gauges in the different districts of the WSS were located (gauge redundancy). Secondly, the balance equations that provide an additional value of the measured physical variables were identified (analytical redundancy). Thirdly, different types of error were simulated for the level and flow rate gauges installed in the WSS: (i) random errors, (ii) drifts, and (iii) critical gauge failures. Finally, simulations of the coupled hydraulic and decision model were performed.

In Figure 3, the algorithm for error detection is applied to level measurements at tank S1. As introduced in Figure 2a, two level sensors are available for each tank. In this simulation, the level sensor MH-2 was disturbed by statistical errors related to instrumental accuracy. The sensor MH-2 was further disturbed by drifts (1 in Figure 3a), random oscillations (4 in Figure 3a) and transmission interruptions (5 in Figure 3a). Moreover, the signal was set on the minimum (2 in Figure 3a) and full-scale (3 in Figure 3a) constant values to simulate critical failures of the sensor.

A third value of the tank level was obtained using a mass balance equation of the flow rate measurements into and out of the tank. The flow rate meters were also disturbed by random errors. As shown in Figure 3a, the level measured by sensor MH-2 is almost equal to the value resulting from the balance equation. On the other hand, the level measured by MH-1 considerably differs from the previous ones, due to instrumental failures. By means of the residual analysis, the developed algorithm detects with high precision the presence of errors in the measurements transmitted by MH-1. In Figure 3b, for each level value, error detection is highlighted with a red signal. Moreover, the algorithm selects the most reliable measurement to be used in the control operations of the WSS in real-time (green signal in Figure 3b). Under ordinary conditions, the algorithm alternatively selects the data measured by the two level gauges. In case of error detection for MH-1, the measurement transmitted by MH-2 is the only one to be selected. In this way the algorithm guarantees resilience in the operations of the turbine T1, whose regulation is based on the water level in tank S1 (*Fellini et al.*, 2018).

Similar results were obtained by applying the method to the other level and flow meters in the WSS.

The developed method is able to isolate errors only in the case of a single failure in the measurements involved in each system of three equations used for the residual analysis (e.g., equation system in Figure 1a). In the case of multiple simultaneous errors the algorithm is not robust.

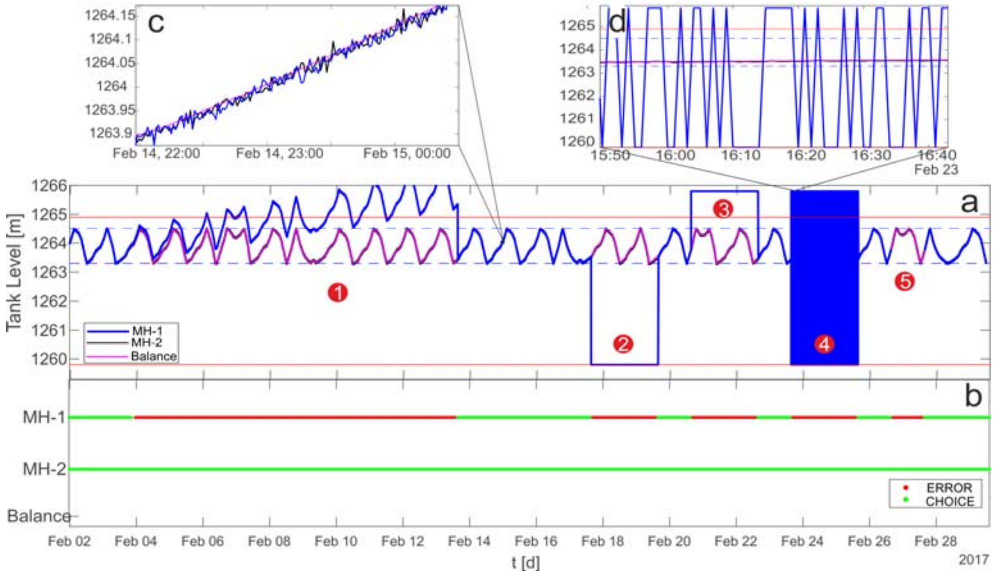


Figure 3: a) Level values from level gauges MH-1 and MH-2 and from a balance equation of the flow rate measurements into and out of the tank. The red lines are the maximum and minimum water level in tank. The blue dotted lines are the regulation thresholds (*Fellini et al.,* 2018). Measurements from MH-1 experience drift (1), random oscillations (4), transmission interruption (5) and settle on the full-scale (3) and minimum (2) constant values. b) Error detection and measurement selection for the control operations in the WSS. c)-d) Measurement signals details.

4 CONCLUSION

In this work, an algorithm is proposed for real-time evaluation of data measured in the supervisory control system (SCS) of a modern WSS. The WSS faces multiple challenges: water supply over a large area, hydropower generation and coordination among multiple local water supply systems. Therefore, an automated remote control based on reliable flow rate and level measurements is crucial. The developed algorithm compares redundant data obtained from both redundant gauges and analytical models. By means of the residual analysis, failures and gross errors are detected in the considered measurements. Moreover, the algorithm performs a real-time selection of the most reliable measurements to be used in the control operations. The effectiveness of the method was assessed through numerical simulations of a coupled hydraulic and SCS model of the WSS. Results showed that high precision error detection is possible when a single failure occurs in the redundant measurements of the same physical variable. Moreover, the algorithm guarantees continuity in the operations of the WSS and the safety and the reliability of the system are increased. Further studies are required in the near future to extend the method to the case of simultaneous failures in redundant gauges.

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