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Limnimeter and rain gauge FDI in sewer networks using an interval parity equations based detection approach and an enhanced isolation scheme

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ABSTRACT

In this paper, a methodology for limnimeter and rain-gauge *fault detection and isolation* (FDI) in sewer networks is presented. The proposed model based FDI approach uses interval parity equations for fault detection in order to enhance robustness against modelling errors and noise. They both are assumed unknown but bounded, following the so-called *interval* (or set-*membership*) approach. On the other hand, fault isolation relies on an algorithm that reasons using several fault signature matrices that store additional information to the typical binary one used in standard FDI approaches. More precisely, the considered fault signature matrices contain information about residual fault sign/sensitivity and time/order of activation. The paper also proposes an identification procedure to obtain the interval models used in fault detection that delivers the nominal model plus parameter uncertainty is proposed. To exemplify the proposed FDI methodology, a case study based on the Barcelona sewer network is used.

1. Introduction

Sewer networks are complex large-scale systems which require highly sophisticated supervisory-control systems to ensure that high performance can be achieved and maintained under adverse operating conditions. Most cities around the world have sewage systems that combine sanitary and storm water flows within the same network. This is why these networks are known as *Combined Sewage Systems* (CSS). During rain storms, wastewater flows can easily overload these CSS, thereby causing operators to dump the excess of water into the nearest receiver environment (rivers, streams or sea). This discharge to the environment, known as *Combined Sewage Overflow* (CSO), contains biological and chemical contaminants creating a major environmental and public health hazard. Environmental protection agencies have started forcing municipalities to find solutions in order to avoid those CSO events. A possible solution to the CSO problem would be to enhance existing sewer infrastructure by increasing the capacity of the wastewater treatment plants (WWTP) and by building new underground detention tanks. But, in order to take profit of these expensive infrastructures, a highly sophisticated *real-time control* (RTC) scheme is also necessary which ensures that high performance can be achieved and maintained under adverse meteorological conditions (Schütze et al., 2004; Marinaki and Papageorgiou, 2005). The advantage of RTC applied to sewer networks has been demonstrated by an important number of researchers during the last decades. Comprehensive reviews that include a discussion of some existing implementations are given by Schilling et al. (1996), Schütze et al. (2004) and cited references therein, while practical issues are discussed by Schütze et al. (2002), among other. The RTC scheme in sewage systems might be *local* or *global*. When local control is applied, flow regulation devices use only measurements taken at their specific locations. While this control structure is applicable in many simple cases, in a big city, with a strongly interconnected sewer network and a complex infrastructure of sensors and actuators, it may not be the most efficient alternative. Conversely, a global control strategy, which computes control actions taking into account real-time measurements all through the network, is likely the best way to use the infrastructure capacity and all the available sensor information. The multivariable and large-scale nature of sewer networks has lead to the use of some variants of Model Predictive Control (MPC), as global control strategy (Gelormino and Ricker, 1994; Cembrano et al., 2004; Pleau, 2005; Marinaki and Papageorgiou, 2005; Ocampo-Martínez, 2008).

The global RTC need to operate in adverse meteorological conditions involves, with a high probability, sensor and actuator malfunctions (faults). This problem calls for the use of an on-line *fault detection and isolation* (FDI) system able to detect such faults and correct them (if possible) by activating fault tolerance mechanisms, as the use of soft sensors or using the embedded tolerance of the MPC controller, that avoids that the global RTC should be stopped every time that a fault appears. According to Schütze et al. (2004), this is one of the main reasons why today there is a small number of global RTC operating in the world. This

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difficulty has also been assessed by the author when implementing the global RTC in the Barcelona sewer network (Cembrano et al., 2004). This has motivated the research presented in this paper.

In the literature, FDI in sewer networks has already been addressed. In Giuliani et al. (1997), fault detection for rain-gauges is addressed. Fault detection is based on deriving models for the most-correlated rain-gauges (as in the current paper) but adaptive thresholds are generated either on statistical methods or in a heuristic way. In the present paper, interval models are used to generated adaptive thresholds. Regarding fault isolation, In Giuliani et al. (1997), approaches based on DMP and theory of evidence are proposed. The fault isolation approach proposed in this paper, improves DMP approach by using an adaptive threshold generated using the interval model and includes some corrections to the DMP sensitivity formula. The use of Kalman filters and Wald sequential test has been proposed by Piatyszek et al. (2000) as means of detecting limnimeter faults in sewer networks. In all these approaches, a simplified deterministic model of rainfall–runoff transformation is considered. In Boukhris et al. (2001), fault detection for limnimeters using Takagi–Sugeno models is proposed. The problem of fault isolation is based on binary fault signature matrices. In Meseguer et al. (2010), fault detection of limnimeter using interval observers is proposed. No method for estimating parameter uncertainty to obtain interval models is suggested. Fault isolation is based on a discrete-event approach that uses similar factors than the one proposed in this paper.

In the present paper, a simplified model based on the virtual tank modelling approach proposed in Cembrano et al. (2004) is used to model the rainfall–runoff transformation. This conceptual modelling approach based on establishing mass balances in the sewer network catchments avoids the complexity of the physical oriented models based on Saint-Venant equations that are not adequate to be used on-line. To consider the uncertainty in the sewer modelling due to the use of this conceptual approach, a FDI approach based on *interval models* and *methods* is proposed (Puig et al., 2008). Interval methods are very appropriate when the modelling uncertainty is included in the model by means of interval parameters. Moreover, noise can easily handled using the interval methods since only a noise bound is required without any assumption about the statistical distribution. For both reasons, interval methods can be considered as an alternative to *stochastic models* and *methods* (Bassevile and Nikiforov, 2003; Nikiforov, 1998). In Meseguer (2010), interval observers for fault detection have been already proposed for limnimeter fault detection. In this paper, alternatively interval parity equations expressed in regressor form are proposed. The advantage of interval parity equations with respect to observers is that the algorithm proposed in Blesa et al. (2011a) for estimating interval parameters and generating detection thresholds can be used. Interval parity approaches are less computational demanding than observers because the parameters enter linearly in the equations. This fact has already noticed by Ploix and Adrot (2006).

In this paper, the problem of FDI is mainly focused on rain gauges and limnimeters used for the RTC of a sewer network, but could easily being extended to actuator faults or faults in other elements in the network. The proposed fault detection and isolation strategy is based on building an interval model for every instrument. Then, each instrument reading is compared with the prediction provided by its interval model. While, the real measurement is inside the interval of predicted behaviour (or envelope) generated using its interval model, no fault can be indicated. However, when the measurement is outside its envelope, a fault can be indicated (Puig et al., 2008). Once the fault has been detected, a fault isolation procedure is initiated in order to isolate the faulty instrument. The proposed FDI approach introduces also an improved interface between fault detection and isolation that reasons not only using binary information about fault signal activation but also considers residual fault sensitivities and time/order of activation. The need of such improved interface has been motivated because the application of the standard binary interface between fault detection and isolation could lead to wrong diagnosis when the residuals present different sensitivities and order/time of activation after the fault appearance (Combastel et al., 2003). The proposed diagnosis approach in this paper comes from an evolution of the algorithm presented in Puig et al. (2005). In the literature, there have also appeared other proposals following the same spirit as the one proposed by Van den Daele et al. (1997), where the activation of a residual generates an event with a belief and time stamp, among other attributes. Then, a reasoning using a causal graph produces a set of candidate faults ranked from the most to the least probable. In the same line, Ragot and Maquin (2006) proposed an improved fault diagnosis approach based on the fuzzy evaluation of the residuals that considers not only binary information but also signs/sensitivities as well as the persistence of residual activation. This approach has also been applied to a water network.

To exemplify the FDI problem in sewer networks and the proposed FDI methodology, the Barcelona network is used as the case study. Such network has a telemetry system containing 22 rain gauges and more than 100 limnimeters used for the RTC system. In this paper, a representative part of this network is considered.

The organisation of the paper is the following: Section 2 presents how models for FDI in rain-gauges and liminimeters are built and intervals for parameters are estimated. Section 3 overviews the proposed FDI scheme. Sections 4 and 5 discuss the implementation of the fault detection and isolation modules. Section 6 presents a description of the Barcelona sewer network used as a case study and shows the results obtained using the proposed FDI scheme. Finally, Section 7 closes the paper with the conclusions.

2. Interval models for FDI in sewer networks

Rain gauges and limnimeters are the two type of sensors used in the RTC of sewer networks: the first type measures rain intensity while the second one measures the sewer water level. In general, when detecting faults in sensors two strategies are possible: *hardware redundancy* based on the use of redundant (extra) sensors and *analytical redundancy* based on the use of a mathematical model that combines measurements from other correlated sensors or from the same sensor in past instants (Patton et al., 2000). In critical systems (space aircrafts, aeroplanes,…) hardware redundancy is preferred. But, in large scale systems (as the case of sewer networks), the use of hardware redundancy is very expensive and increases the number of maintenance and calibration operations. That is the reason why analytical redundancy has been proved to be a good and cheaper alternative. This is the approach followed in this paper.

2.1. Modelling limnimeters

Typically, in sewer networks, sewage level is measured instead of flow. There are two reasons that can explain this fact. First since the level is measured using ultrasonic waves, limnimeters do not have contact with the sewage flow (Fig. 1), and consequently, the required maintenance is cheaper. Second, limnimeters are cheaper than flowmeters. Ultrasonic limnimeters generates an acoustic pulse that is transmitted from the transducer and then it is reflected back from the surface of the liquid. The transit time is then converted into the current output, which is directly proportional to the fluid level. From level measurements, the flow in a sewer can be estimated assuming steady-uniform flow and using the Manning formula calibrated using