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Model-free fault detection and isolation of a benchmark process control system based on multiple classifiers techniques—A comparative study

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ABSTRACT

This paper presents a combined data-driven framework for fault detection and isolation (FDI) based on the ensemble of diverse classification schemes. The proposed FDI scheme is configured in series and parallel forms in the sense that in series form the decision on the occurrence of fault is made in FD module, and subsequently, the FI module coupled to the FD module will be activated for fault indication purposes. On the other hand, in parallel form a single module is employed for FDI purposes, simultaneously. In other words, two separate multiple-classifiers schemes are presented by using fourteen various statistical and non-statistical classification schemes. Furthermore, in this study, a novel ensemble classification scheme namely blended learning (BL) is proposed for the first time where single and boosted classifiers are blended as the local classifiers in order to enrich the classification performance. Single-classifier schemes are also exploited in FDI modules along with the ensemble-classifier methods for comparison purposes. In order to show the performance of proposed FDI method, it was also tested and validated on DAMADICS actuator system benchmark. Besides, comparative study with the related works done on this benchmark is provided to show the pros and cons of the proposed FDI method.

1. Introduction

Nowadays, reliability and availability have become crucial issues in process control system design and received great attention during last decades. An intelligent diagnostics is one of the essential components of modern process control system. Due to manufacturing defects, erosion and corrosion, and other kinds of performance deterioration in system components, and in order to prevent major collapses in plant and system shutdowns, "early" diagnosis of faults is an important factor (Nozari, Simani, & Shoorehdeli, 2012). There are two approaches that contribute to increase the availability and reliability of industrial process plants: (1) using more solid constructions, redundant equipment that yields additional cost per plant, (2) control systems based on advanced FDI and/or fault tolerant control (FTC) that results in increased costs in development phase (Odgaard, 2014). However, the FDI approach has received much of attention as the major contributor to find a simple, low-cost fix to remedy the maintenance problem associated with the industrial process plants. Therefore, it is important to design diagnostics that can automatically detect and isolate occurred faults, maintain the overall functionality of system, and provide an acceptable performance for the faulty system without an unnecessary need to shut down the system.

Generally, a fault diagnosis system is a monitoring system that is used to detect faults and diagnose their location and magnitude in a system (Castaldi, Mimmoa, & Simani, 2014). The diagnosis system performs the following tasks: fault detection (FD)—to indicate if a fault occurred or not in the system, fault isolation (FI)—to determine the kind, location and time of detection, and fault identification—to estimate the time behavior of the fault signal. The first two tasks of the system: fault detection and isolation are considered the most important. Fault diagnosis is then very often considered as fault detection and isolation (Simani & Fantuzzi, 2006). Moreover, fault diagnosis task can be realized in terms of model-based, knowledge-based, and data-driven approaches which the latter is also referred to as model-free approach (Guglielmi, Parisini, & Rossi, 1995) and considered in this research. The basic idea is to monitor on-line the measurements of the control system variables without the need for defining explicit dependence laws

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Nomenclature and Abbreviations

P51_05	P1 — juice pressure (value inlet)
P51_06	P2 — juice pressure (value outlet)
T51_01	T — juice temperature (value outlet)
P51_01	F — juice flow (1st evaporator inlet)
LC51_03CV	CV — control value (controller output)
LC51_03X	X — servo motor rod displacement
LC51_03PV	PV — process value (juice level 1st evaporator)
TC51_05	Juice temperature (1st evaporator inlet)
T51_08	Juice temperature (1st evaporator outlet)
D51_01	Juice density (1st evaporator inlet)
D51_02	Juice density (1st evaporator outlet)
F51_01	Steam flow
PC51_01	Steam pressure
T51_06	Steam temperature
T51_03	Vapor pressure
T51_07	Vapor temperature

in time-domain among them. By analysis of the measured variables the operator can decide about the operating mode of the plant and raise alarms. In this context, sometimes the problem can be assimilated to a pattern-recognition problem (see, *e.g.*, Guglielmi et al., 1995). In order to develop data-driven methods, measurements from several input–output process variables are recorded in fault-free and faulty operating conditions from the real process plants. However, in most cases, it is not possible to acquire much of data from the real operating process and it will be more difficult to collect data in faulty operating situation due to safety issues. Therefore, it is more commonplace to employ high-fidelity full-scale simulator of the process plants which is tested and validated against real measurements to collect as much data as required in different operating conditions. Then, the fault diagnosis can be considered as classification problem to assign each pattern of process variable vector to one of the pre-specified class of process operating condition (i.e., nominal and faulty operating situations). In the available literature, many types of classification techniques based on a single classifier have been introduced and employed to address the FDI problems of industrial process control systems. They can range from classic to intelligent methods including the similarity between patterns in the feature space, probabilistic methods, methods based on black box models and/or their combinations (Kuncheva, 2004). In the last few years, multiple classifier algorithms have become the most important directions of the research in the domain of supervised learning and can find critical roles in developing accurate model-free process monitoring systems. The key aspects of these algorithms are to generate and then combine an ensemble of classifiers, where each classifier is trained on a different sub-set of the data (Rokach, 2010).

This paper aims at presenting a general model-free diagnostic system for MIMO nonlinear process plants where reliability and safety issues represent a great concern. Toward this goal, a data-driven fault diagnosis system is designed for nonlinear process plants and tested on a complex process control valve, regulating the inlet flow to the first evaporator of a three-stage evaporation process unit, subsystem found in the sugar factory Lublin, S.A. in Poland, and studied under the European Commission project DAMADICS (Development and Application of Methods for Actuator Diagnosis in Industrial Control Systems) (DAMADICS, 2004). Both the control valve and the evaporator models are also experimentally tuned and validated by means of real industrial process data (Bartys, Patton, Syfert, de las Heras, & Quevedo, 2006) and a full-scale simulator is available to generate much of data from all normal and faulty operation conditions. It must be also noted that control valve malfunction is significant when these components are installed in harsh environments like high temperature, humidity, pollution, chemical solvents etc. The determination of the development of small (incipient-hard to detect) (Nozari et al., 2012; Simani & Fantuzzi, 2006) faults before they become serious clearly an important influence on the control valve's predicted lifetime. Valve faults causing process disturbance and shutdown are of major economic concern and shutdown is of major economic concern and can do sometimes be an issue of safety and environmental pollution. In any case, when actuators do not perform correctly, the final product quality is influenced. Therefore, the monitoring of the development of incipient faults is an issue not only for predicting maintenance schedules but also for monitoring the performance of the process concerned (Kalisch, Przystałka, & Timofiejczuk, 2015). In the reviewed literature, while there are many research methods proposed for model-based FDI of industrial control valves particularly that one proposed in DAMADICS benchmark (see, for example, Isermann, 1998; Kourd, Lefebvre, & Guersi, 2013; Mendonça, Sousa, & Sá da Costa, 2009; Puig et al., 2006; Stancu, Puig, Quevedo, & Patton, 2003; Witczak, 2006), a few research efforts have been dedicated to model-free FDI of this industrial actuator system as opposed to the more common model-based approaches. In most cases, proposed data-driven FDI schemes were elaborated in terms of a single classifier, which returns a diagnostic signal corresponding to fault or faultless states of the device. For example, in Sundarmahesh and Kannapiran (2013), a single neural network-based classification scheme was proposed to tackle the FDI problem of this benchmark. A model-free faults detection and identification method based on the clusterisation of the multiple diagnostic signals by employing self-organizing maps is presented in Katunin, Amarowicz, and Chrzanow (2015). A Two-stage data-driven FDI method on the basis of single perceptron neural network classifier was introduced in Rokach (2010). In Calado, Sá da Costa, Bartyś, and Korbicz (2006), a fuzzy qualitative simulation algorithm used for FD purposes, coupled with a hierarchical structure of fuzzy neural networks used to perform the fault isolation task on DAMADICS benchmark. A model-free FDtechnique based on the use of a specific spectral analysis tool, namely, the Squared Coherency Functions (SCFs) was proposed in Previdi and Parisini (2006). The detection of a fault was achieved by on-line monitoring the estimate of the squared coherency function, which is sensitive to the occurrence of significant changes in the plant dynamics. The alarm thresholds are based on the estimates of the confidence intervals of the SCF. The Moreover, ensemble-based classification approach has also been exploited to tackle the FDI problem of industrial actuator systems. In Oliveira and Sá da Costa (2011), a hierarchical diagnosis structure based on ensemble learning with specific feature extraction steps for each branch is presented and Radial Basis Function networks are used as local classifiers. Finally, fuzzy logic aggregates the results for each fault. In Chopra and Vajpai (2011), a stochastic gradient boosted decision trees based classifier has been developed for the DAMADICS benchmark problem and generates a series of trees with the output of one tree going into the next tree in the series. In Kalisch et al. (2015), ensemble classification schemes are compared to single classifier schemes to detect and isolate abrupt faults of this benchmark problem. Classic classification algorithms such as K-nearest neighborhood, naive Bayes, decision tree, and rules inductions are considered as local and base classifiers in bagging and boosting classification methods. However, although only abrupt faults were considered for detection and isolation purposes, very promising results were not presented and cases of misclassifications were reported.

To our best knowledge, lesser research efforts has been devoted to data-driven FDI of DAMADICS benchmark compared to proposed model based methods. However, among the available model-free FDI methods on process actuator systems, a few ensemble-based classifier solutions have been proposed to tackle this challenging problem. However, it must be noted that data-driven FDI methods can find critical roles when it is not possible to acquire an accurate model of the process in reality. Thus, designing a general model-free FDI system for nonlinear process plants represents a great importance in reliability context. According to the available literature, in all the proposed model-free methods, detection and isolation of incipient faults were excluded. This can be due to the