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Experimental validation of an actuator fault tolerant control system using virtual sensor: Application in a double pipe heat exchanger

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ABSTRACT

This work presents an actuator fault tolerant control (FTC) system applied in a counter-current double pipe heat exchanger. The heat exchanger has two input variables which are, cold and hot water flow rates. The main actuator manipulates the cold water flow rate in order to control the hot water temperature. The goal of this work is to keep in continuous operation the counter-current double pipe heat exchanger, even if the main actuator is stuck-open. In case of failure on the main actuator, it is proposed to control the process with the second input variable (by manipulating the hot water flow rate). To achieve our aim, we designed an FTC system based in a fault detection and isolation (FDI) system and a Model Following Control (MFC). To develop the FDI system an adaptive nonlinear observer to estimate the flow rates in the heat exchanger for both streams (hot and cold) was implemented. The FDI is performed by the comparison between the flow rate estimation (by the adaptive nonlinear observer) and the flow rate provided by the control law. The nonlinear flow rate estimation is needed because the real plant does not have digital flowmeters to measure the flow rates online. The FDI system allows to detect and isolate the fault actuator then, the control signal and the failure accommodation is realized by the MFC. The results showed that it is possible to keep the heat exchanger in continuous operation even if the main actuator is stuck-open.
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1. Introduction

The new technological issues for processes have sophisticated control systems to keep the quality, the efficiency of the processes and safety for the operators and the equipment. A conventional feedback control designed for complex systems can be inefficient and/or unstable if an actuator or sensor fault occurs during the processes operation. To supervise a process and analyze a possible failure in a sensor, actuator or equipment, there are different control approaches to detect, diagnose and/or isolate a fault. These kinds of systems are called Fault Detection and Diagnosis (FDD), fault detection and isolation.

For a dynamic process, the FDD is a technique used to detect a failure in the process or in a physical element of the equipment, such as a sensor or an actuator. Furthermore, this

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technique can identify and locate the faulty element or elements. The FDD analysis gives important information to the operator about the magnitude of the failure. So, there are three main objectives of the FDD:

- *Fault detection*. The system provides the information about the presence of a failure and its moment of occurrence.
- *Fault location*. The system provides the information about the kind of the fault, and the identification of the faulty element.
- *Fault estimation*. The system provides the information about the magnitude and the behavior of the fault.

The FDI is a technique used in FTC systems, which provides important information to the FTC system about the faults in the process, and allows the reconfiguration of the control law in the FTC. The function of the FDI is to detect, locate and isolate the faulty element.

An FTC system is capable of ensuring the reliability and availability of the process even in a sensor or actuator fault (Zhang and Jiang, 2008). The FTC systems are classified in passive and active:

- *Passive fault tolerant control*. These systems consist in a robust design of feedback control to make the process immune to certain faults (Patton, 1997). The fault tolerance, in this case, needs a controller design that is insensitive (robust) to a restricted set of faults, where the types of faults are considered in the design stage of the controller. In the passive FTC, a single control law is designed (normal or fault operation) (Puig et al., 2010).
- *Active fault tolerant control*. These systems consist in the online diagnostic failure. So, it is necessary to include an FDI system to realize the accommodation or reconfiguration of control law. In this system, an emergency stop can be considered depending on the severity of the fault.

In the chemical industry, the heat exchanger devices are widely used. Several works have been addressed in FDD and FTC systems design. In Escobar et al. (2015) the authors report the implementation of the sensor fault compensation system via software sensors with application in a heat pump's helical evaporator. To realize this work the author used analytical redundancy in order to isolate the faulty sensor by a numerical estimation given by a high-gain nonlinear observer, in this work, the authors present satisfactory experimental results in the fault tolerant control implementation. In Adam-Medina et al. (2013) it was presented an FDI system using second order sliding mode observers with application in a counter-current double pipe heat exchanger. The authors used a bank of two-second order sliding mode observers, in order to realize analytical redundancy. Other works proposed in fault detection and fault tolerant control were presented in Mhaskar et al. (2006b, 2006) and Mhaskar et al. (2008). In Mhaskar et al. (2006b), was presented an integrated faultdetection and fault tolerant control system for nonlinear processes input constraints subject to control actuator failures. The authors consider a family of candidate control configurations characterized by different manipulated inputs. For each control configuration, the authors designed a Lyapunov-based controller, which enforces asymptotic closed-loop stability in the presence of constraints, and the constrained stability region, associated with it, was explicitly characterized. Furthermore, to deal with the problem of lack of the process state measurements, a nonlinear observer was designed to estimate the estates of the process which are then used to implement the state feedback controller and the fault-detection filter. The results in the implementation of the fault detection and fault tolerant control system were satisfactory. Other work presented by Mhaskar et al. (2006), deals with the system/actuator failures in nonlinear processes subject to input constraints. In this work, the authors consider two approaches to deal with fault tolerant control incorporating performance and robustness considerations. Performance considerations were incorporated via the design of a Lyapunov-based predictive controller. To implement the fault tolerant control, the authors have to design a robust hybrid predictive controller for each candidate control configuration that guarantees stability from an explicitly characterized set of initial conditions, subject to uncertainty and constraints. In Mhaskar et al. (2008), the authors proposed a fault detection and isolation filter and fault tolerant control designed by a controller reconfiguration for a multi-input multi-output nonlinear system, in this work the manipulated inputs were subject to constraints for both the state and output-feedback cases, the filters were designed to capture the difference between fault-free evolution of the system and the states observed evolution to detect and isolate faults in the control actuators. The authors devised control reconfiguration rules in order to ensure the performance of the fault tolerant control.

In the control area, the MFC have been widely used since 1970s. In Winsor and Roy (1970) the authors presented a procedure to design a MFC, the proposed technique has concepts of specific optimal control, trajectory sensitive design and perfect model following, the technique is useful when some of the states cannot be conveniently fed back and when the plant, is subject to mathematical modeling inaccuracies. In Young (1978) it was presented a design concept for adaptive MFC, in this work the author used the theory of variable structure systems and sling mode, in order of shaping the error transient responses. Chieng and Stengel (1990) presented a restructurable control using a proportional integral implicit model following. This research was focused on recovering the performance of a system with failed actuators or structural damage; the results demonstrated that the model following is a good candidate for control reconfiguration. In Hua and Ding (2011), the author presented a robust adaptive MFC design scheme for a class of interconnected systems with time delays and multiple dead-zone inputs. The author concludes that the controller is tolerant to any dead-zone inputs and general time-varying delays. In order to realize an FTC system, the author in Cimpoesu et al. (2011) proposed two controllers reconfiguration schemes based on the MFC principles, the implicit model following and explicit model following approaches. Recent works on the MFC are presented in Taniguchi et al. (2014), where the authors designed a MFC of a unicycle mobile robot via dynamic feedback linearization; In Park et al. (2014) it was presented a safe driving algorithm of an electric wheelchair with an MFC. In Shibasaki et al. (2015) the authors presented an MFCS which is based on a switching function where the optimal gain matrix was determined by the LQR method. In Wang and Wu (2015) the authors design an MFC system for a cutting system with time-delay, the design was constructed using an algebraic algorithm of matrices whose elements are polynomials, in this article the authors proved that the resulting closed-loop error system is uniformly ultimately bounded stable. It has been shown that the MFC is a technique widely used to recover the performance of a system when there are

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