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A virtual actuator approach for the fault tolerant control of unstable linear systems subject to actuator saturation and fault isolation delay

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ABSTRACT

This paper presents a fault tolerant control (FTC) strategy for unstable linear systems subject to actuator saturation and fault isolation delay. The solution relies on *virtual actuators*, an active fault-hiding method that reconfigures the faulty plant instead of the controller. The main contribution of the paper consists in the design of the virtual actuators with guarantees that, if at the fault isolation time the closed-loop system state is inside a region defined by a value of the Lyapunov function, the state trajectory will converge to zero despite the appearance of faults within a predefined set. In addition, the design of the nominal controller is performed so as to maximize the tolerated delay between the fault occurence and its isolation. Finally, the theoretical results are demonstrated and illustrated using an example.

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1. Introduction

Real-world actuators are always subject to limits in the magnitude of the manipulated input. The control techniques that ignore these actuator limits can be affected by degraded performance, and may even lead to instability of the closed-loop system. Hence, recent research has focused on the analysis and synthesis of control systems with saturating actuators (Tarbouriech & Turner, 2009; Tarbouriech, Garcia, Gomes da Silva, & Queinnec, 2011). The developed solutions mainly use two approaches: the *two-step* paradigm, also called *anti-windup compensation* (Grimm et al., 2003; Mulder, Kothare, & Morari, 2001), where a controller which does not explicitly take into account the saturation is designed, and then a compensator is added to handle the saturation constraints; and the *one-step* paradigm, also called *direct control design* (Gomes da Silva & Tarbouriech, 2001; Sussmann, Sontag, & Yang, 1994), where the input constraints are taken into account at the controller design stage.

In recent years, fault tolerant control (FTC) techniques have been investigated, with the objective of maintaining the performances under fault occurrence close to the desired ones, and preserving stability conditions in the presence of faults (Blanke, Kinnaert, Lunze, & Staroswiecki, 2006; Noura, Theilliol, Ponsart, & Chamseddine, 2009). Even though fault tolerance can be achieved straightforwardly through the so-called *hardware redundancy*, i.e. by adding redundant actuators and sensors that replace the faulty ones under fault occurrence, the *analytical redundancy* is often preferred in order to decrease the overall economic cost. The existing analytical redundancy approaches are usually classified into passive and active (Jiang & Yu, 2012). The *passive FTC techniques* are control laws that take into account the fault as a system perturbation. Thus, within certain margins, the control law has inherent fault tolerant capabilities, allowing the system to cope with the fault presence. On the other hand, the *active FTC techniques* compensate the faults either by selecting a precalculated control law or by synthesizing on-line a new control strategy. The adaptation of the control law is done by using some information about the fault so as to satisfy the control objectives with minimum performance degradation after the fault occurrence (see Benosman, 2010; Zhang & Jiang, 2008 for a review).

Among the successful active FTC strategies, there is the *fault-hiding* paradigm (Steffen, 2005), where the faulty plant is reconfigured instead of the controller. The advantage of this paradigm, with respect to other active FTC strategies, is that the property of fault tolerance can be added to an existing control scheme, without affecting the other properties, e.g. stability and performance, already attained by the controller under nominal situation. The controller is kept in the loop by inserting a reconfiguration block between the faulty plant and the controller when the fault occurs. The reconfiguration block is chosen so as to hide the fault from the controller point of view, allowing it to see the same plant as before

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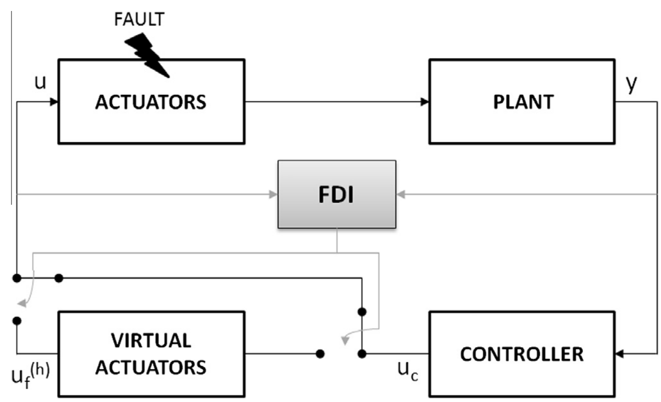

Fig. 1. Virtual actuator FTC concept.

the fault. In case of actuator faults, the reconfiguration block is named *virtual actuator*, because it generates a signal which has the same effect, or approximately the same, as the faulty actuator would have in the nominal system (Lunze & Steffen, 2006) (see Fig. 1 for a scheme illustrating the virtual actuator FTC concept). Initially proposed in a state-space formulation for linear time invariant (LTI) systems (Lunze & Steffen, 2006), this active FTC strategy has been successfully extended to linear parameter varying (LPV) (Rotondo, Nejjari, & Puig, 2014), Takagi–Sugeno (Dziekan, Witczak, & Korbicz, 2011), piecewise affine (Richter, Heemels, van de Wouw, & Lunze, 2011), Lipschitz (Khosrowjerdi & Barzegary, 2013) and Hammerstein-Weiner (Richter, 2011) systems. An equivalent formulation in input–output form has been recently proposed in Blesa, Rotondo, Puig, and Nejjari (2014).

It is important to consider the actuator saturation constraints in the application of an FTC strategy, especially when actuator faults are considered. In fact, fault tolerance against actuator faults is usually achieved redistributing, in some way, the control effort corresponding to the faulty actuators among the remaining healthy ones. This redistribution may lead to saturation of both the faulty and the healthy actuators. Thus, if this fact is neglected in the FTC system design, severe performance degradation or instability may occur (Fan, Zhang, & Zheng, 2012). Some recent works have considered the problem of FTC systems subject to actuator saturations. Benosman and Lum (2009) show that failures resulting from loss of actuator effectiveness in systems with input saturations can be dealt with in the context of the absolute stability theory framework. Zuo, Ho, and Wang (2010) present two kinds of fault tolerant controllers (fixed-gain and adaptive) for singular systems subject to actuator saturation. Both of these two controllers are in the form of a saturation avoidance feedback. Xiao, Hu, and Zhang (2012) develop a fault tolerant control scheme that can achieve attitude tracking objective for a flexible spacecraft in the presence of partial loss of actuator effectiveness fault and actuator saturation using sliding mode control. The solution proposed by Mhaskar, McFall, Gani, Christofides, and Davis (2008) avoids to use the failed control actuators in the event of a fault. Also, concepts such as *graceful performance degradation* (Jiang & Zhang, 2006; Zhang, Jiang, & Theilliol, 2008) and *reference reconfiguration* (Benosman & Lum, 2009; Theilliol, Join, & Zhang, 2008) have been introduced in the context of FTC of systems subject to actuator saturations. However, only a few works have considered this problem for unstable systems. Stoustrup and Niemann (2004) has proposed a linear time varying (LTV) fault tolerant compensator, using the relevant ability of LTV compensators to achieve simultaneous stabilization of several systems. An active FTC scheme based on gain-scheduled $\mathcal{H}_\infty$ control and neural network for unstable systems has been proposed by Weng, Patton, and Cui (2006). Finally, Hu, Xiao, and Friswell (2011) develop a robust fault tolerant scheme based on variable structure control for an orbiting spacecraft with a combination of unknown actuator failures and input saturation.

However, even though an active FTC system can react to faults more effectively than a passive FTC system can do, passive FTC techniques have been preferred to the active ones when dealing with unstable systems (Fan et al., 2012; Hu et al., 2011; Stoustrup & Niemann, 2004). In fact, the active FTC strategies require a fault detection and isolation (FDI) module, and when unstable systems are considered, the time delay between the appearance of the fault and the moment in which the active strategy is activated (at the fault detection or isolation time) may destabilize the system. According to our knowledge, Weng et al. (2006) is the only work dealing with active FTC for unstable system. However, in this reference, the issues arising from the FDI time delay were not considered. Also, another issue that has not been considered is the fact that, when dealing with unstable systems, the stability properties guaranteed by the control design are *regional*, i.e. hold only for inputs up to some size or for initial states inside a region of the state space (Wu & Lu, 2004). The fault appearance, and the subsequent control system reconfiguration brought by the active FTC strategies change the regional stability properties of the control system, so it is necessary to take into account this fact explicitly when the system is subject to actuator saturations.

The main contribution of this paper consists in the design of an active FTC strategy for unstable systems subject to actuator saturation. Under the assumption that a nominal controller has been already designed using the direct control design paradigm to take into account the saturations, virtual actuators are added to the control loop for achieving fault tolerance against a predefined set of possible faults. In particular, faults affecting the actuators and causing a change in the system input matrix are considered. The design of the virtual actuators is performed in such a way that, if at the fault isolation time the closed-loop system state is inside a region defined by a value of the Lyapunov function, the state trajectory will converge to zero despite the appearance of the faults. Also, it is shown that it is possible to obtain some guarantees about the tolerated delay between the fault occurrence and its isolation. Moreover, the design of the nominal controller can be performed so as to maximize the tolerated delay.

It should be pointed out that, although saturations can be included within the Hammerstein-Weiner formulation of the virtual actuators, the approach proposed in this paper can be distinguished from the one introduced in Richter (2011) since less restrictive assumptions are required. In particular, some delay in the fault isolation is accepted, and the system matrix could be non-Hurwitz. In fact, although applicable to stable systems, the approach proposed hereafter focuses on the unstable ones.

The paper is structured as follows. Section 2 recalls some known results that will be used throughout the paper. Section 3 states the problems, that are solved in Section 4. The theoretical results are illustrated using an example in Section 5. Finally, the main conclusions are drawn in Section 6.

Notation: For a given matrix $M \in \mathbb{R}^{n_r \times n_c}$, the ith row will be denoted as M_i, and the element located in its ith row and jth column as $M_{i,j}$. For brevity, symmetric elements in a matrix are denoted by $*$ and $M + M^T$ will be indicated as $He\{M\}$. If a matrix $M \in \mathbb{R}^{n \times n}$ is symmetric, then $M \in \mathbb{S}^{n \times n}$. I and O denote the identity matrix and the zero matrix of appropriate dimensions, respectively. A matrix $M \in \mathbb{S}^{n \times n}$ is said *positive definite* ($M \succ 0$) if all its eigenvalues are positive, and *negative definite* ($M \prec 0$) if all its eigenvalues are negative. Moreover, the symbol $\otimes$ denotes the Kronecker product and $\dagger$ denotes the Moore–Penrose pseudoinverse.

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