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# Linear adaptive actuator failure compensation for wing rock motion control

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**Abstract**

In this paper, a novel adaptive actuator failure compensation control strategy is developed for wing rock motion control in the presence of both system and actuator failure uncertainties. The proposed strategy can compensate for both total and partial loss of effectiveness. A proportional actuation scheme of redundant aileron segments is used. This allows bringing the faulty multi-input single-output nonlinear system into an equivalent perturbed single-input single-output system. Afterward, an adaptive actuator failure compensation control scheme is developed around a linear approximation of an ideal feedback linearization controller. A failure estimation and compensation term is appended to this controller to account for possible actuator failures. Closed-loop stability and tracking performance are proved based on Lyapunov theory and a piecewise analysis is also introduced to show that stability properties hold despite the presence of parameter jumps caused by abrupt actuator failures. Simulation results on a small scale wind tunnel based wing rock model with redundant actuators show the effectiveness of the proposed adaptive control strategy.

**Keywords:** Wing rock; Adaptive control; Actuator failures; Redundant actuators; Nonlinear systems.

## 1. Introduction

As a result of the increasing demands for performance, precision and higher maneuverability, control systems has become more complex. Thus, failures have become more common, especially in aircraft and spacecraft control systems [1,2]. Failures can take place at different locations within the control loop. They can appear at the plant itself, at the sensors or at the actuators as illustrated in Fig. 1. Actuator failures may lead to severe performance deterioration or even system instability. They can cause catastrophic accidents involving human lives and millions worth equipment if they are not handled properly using appropriate control designs [3]. Recently, actuator failure compensation has become an active area of research that has undergone remarkable progress in both theory and practice. Various actuator failure compensation control designs have been proposed in the research literature. These techniques generally fall into two categories, the passive approaches and the active approaches [3–5]. In the passive approaches, a fixed controller is designed by considering a set of predefined actuator failures. These approaches are generally based on the robust control theory and aim to optimize system's performance under actuator failures using linear quadratic *(LQ)* control designs and $H_\infty$ [6,7] or using convex optimization based on linear matrix inequalities *(LMI)* [8]. These techniques are limited in that they deal only with a restricted set of failures [4]. On the other hand, active actuator failure compensation approaches are designed to take action at the time of failure occurrence. Among these approaches one can find multiple model based designs [9–11], fault diagnosis and isolation (FDI) designs based residual generation or state observers [3,12], fuzzy logic and artificial neural networks techniques [13,14], and adaptive control based designs [2,5,15–27].

Adaptive control provides adaptation mechanisms to adjust controllers to cope with parametric, structural and external disturbances. The adaptive control approach has been extensively used to design controllers for systems with actuator failures. Many classical linear and nonlinear adaptive control techniques have been extended and customized to compensate for actuator failures [5]. A recent overview on adaptive actuator failure compensation was also presented in [15]. In [16,17], the authors proposed adaptive control schemes for linear redundant systems with lock in place failure types for state and output tracking. In [18,19], the authors proposed adaptive control schemes for multivariable nonlinear systems with unknown actuator failures using feedback linearization techniques. In [20,21], the authors proposed an adaptive backstepping control schemes for a class of parametric strict feedback systems with unknown actuator failures. In these works, system parameters as assumed to be known or partially known, i.e. defined as a product of known nonlinear functions with unknown

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