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Direct adaptive control of a flexible spacecraft with disturbances and uncertain actuator failures

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ABSTRACT

This paper addresses the design of a new adaptive attitude tracking control strategy for a flexible spacecraft system in the presence of external disturbances and uncertain failures of redundant reaction wheels. The proposed strategy does not depend on the exact model of the spacecraft and can compensate for a more general class of time-varying and state-dependent failures that reaction wheels may undergo in a practical environment. The controller is built around an integrated adaptive approximation based design that accommodates for both system and actuator failure uncertainties. The controller parameter update law is derived to minimise the control prediction error. Unlike most existing actuator failure compensation techniques which are limited to special cases of actuator failures, the proposed controller can compensate for a larger set of actuator failures with time-varying patterns. Closed-loop system stability and tracking performance are proved using Lyapunov stability theory. Parameter jumps caused by abrupt failures are also taken into consideration during the stability proof. A simulation study is performed on a spacecraft with flexible solar array actuated by redundant reaction wheels. The results show the effectiveness and feasibility of the proposed actuator failure compensation controller compared to other controllers from the literature.

1. Introduction

The design of attitude controllers for spacecraft systems is a challenging task, this is due to stringent requirements for high attitude pointing accuracy and autonomy needed to ensure space missions success [1,2]. An efficient spacecraft attitude controller should be able to deal with inertia uncertainties and external disturbances inherent to those systems [2,3]. In addition, modern spacecraft systems have become more complex and intricate because they involve an increasing number of actuators and sensors. As a consequence, their vulnerability to failures and malfunctions has increased as well. Failures are malfunctions that can take place at different locations within the control system, they can occur at the actuators, at the sensors or at the plant itself [4]. In a spacecraft system, actuators such as reaction wheels and thrusters are more likely to fail during the course of operation [5–7]. Their failure can lead to severe performance degradation, and sometimes system instability resulting in mission failure or/and catastrophic accidents [3]. Therefore, reliability, resilience and fault tolerance capabilities are important issues to be taken seriously when designing attitude control systems for spacecraft.

From the system's architecture viewpoint, reliability and fault tolerance can be increased through actuation redundancy. In a spacecraft, redundancy can be achieved via backup reaction wheels or redundant thrusters [7,8]. However, the existence

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Nomenclature

$\boldsymbol{\omega} = [\omega_1, \omega_2, \omega_3]$	angular velocity of the spacecraft with respect to inertial frame I
I	inertial frame, B: Body fixed frame, O: Orbital frame
ω_0	orbital rate of the spacecraft
ϕ, θ, ψ	roll, pitch and yaw angles of the spacecraft respectively
$\mathbf{J}$	inertia matrix of the spacecraft
$\mathbf{J_s}$	moment of inertia of the reaction wheel
$\boldsymbol{\Omega}_\mathbf{s}$	angular velocity of the reaction wheel
$\boldsymbol{\delta}$	coupling matrix between elastic structures and rigid body of the spacecraft
$\boldsymbol{\eta}$	modal displacements vector
$\boldsymbol{\Lambda}$	modal frequency
$\mathbf{T_d}$	external disturbances torque
$\boldsymbol{\xi}$	modal damping
$\mathbf{R}$	reaction wheels distribution matrix
$\boldsymbol{\rho}$	reaction wheel effectiveness
$\mathbf{e}$	output tracking error
$\mathbf{s}$	filtered output tracking error
$\mathbf{x}$	state vector of the spacecraft model
$\mathbf{u} = -\mathbf{J_s}\dot{\boldsymbol{\Omega}}_\mathbf{s}$	control torque provided by reaction wheels

of redundancy may bring more challenges for control design when the actuator failure information is not complete. In other words, redundancy may not be sufficient without an intelligent controller that distributes the control effort among healthy actuators in case one or more actuators fail [9,10]. From the system's dynamics viewpoint, actuator failures may introduce additional uncertainties. For instance, when some actuators fail, the mapping from normal inputs (healthy actuators) to the outputs experiences significant changes [10]. Furthermore, actuator failures may introduce new disturbances to the system, which will influence system performance.

In recent years, the problem of actuator failure compensation has received a considerable attention as evidenced by the abundant research literature. An early review of recent research works was provided by Zhang and Jiang [11]. Many known control techniques have been tailored to solve the problem of actuator failure compensation. These techniques fall into two categories: passive and active approaches [4,11,12]. Passive approaches use fixed feedback control laws that are robust with respect to possible system faults [11,12]. Generally speaking, passive approaches are more conservative and limited in dealing effectively with a larger set of actuator failures. In order to remedy the limitations of the passive approaches, active approaches were introduced. Most active actuator failure compensation approaches rely on a fault diagnosis and isolation (FDI) module to monitor the performance of the controlled system and to detect, isolate and estimate the faults in the controlled system [4,13]. Based on fault information, the control law is reconfigured online using techniques such as multiple model based designs [14,15], neural networks and fuzzy logic based designs [16,17]. In [18], a multiple model design is proposed for spacecraft with actuator failures. In [19], a sliding mode fault tolerant controller is developed for electric vehicles with failures in wheels. In [20], new fractional order fault tolerant controller was also proposed in which a super twisting fault estimator is used.

Recently, adaptive control has been widely used in dealing with the problem of controller designs for systems with uncertainties, actuator failures and constraints [10,21–29]. The most advantage of adaptive techniques is that they update the controller online without the need for an explicit FDI module. Besides, direct adaptive control has the advantage of not requiring a quantitative knowledge of the system model, many designs for nonlinear and multivariable systems has been proposed in recent years [28–34], these techniques are usually based on adaptive approximation using universal function approximators such as fuzzy logic systems and artificial neural networks. On the other hand, data-driven control is another recent trend in control design where the controllers are designed based on Input/output data from the plant [35,36]. This is particularly important when an accurate model of the plant is not available or when the model is too complex making the controller complex as well. Many recent data-driven control designs were proposed in the literature. In [35], a comparative survey between data-driven and model based control and the underlying differences was presented. An overview of data driven linearization iterative learning control (ILC) was proposed in [36]. In [37], a novel high order optimal terminal ILC with iteratively update learning gain was propose. In [38], a data-driven optimal ILC is proposed for a class of nonlinear and non-affine systems. In [39,40] a new initial value compensation data driven ILC was developed with application on a batch reactor and fermenter. It is worth noticing that these works were developed for discrete time systems. Besides, to the authors best knowledge, very rare data-driven control designs were proposed in the field of actuator fault tolerant control except in some works such as in [41–44].

As for spacecraft systems, there are rich results in this regard; adaptive backstepping and sliding mode control techniques are effective and robust to certain types of disturbances and uncertainties. They have also been used to accommodate the partial loss of effectiveness for the flexible spacecraft attitude control system as in [2,3], and for a rigid spacecraft as in