Acta Astronautica 139 (2017) 181–188

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Agent-based algorithm for fault detection and recovery of gyroscope's drift in small satellite missions

Johan Carvajal-Godinez, Jian Guo *, Eberhard Gill

Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, Delft, The Netherlands

ARTICLE INFO

Keywords:
FDIR
Multi-agent systems
Onboard software architecture
Independent component analysis
Gyroscope drift bias correction

ABSTRACT

Failure detection, isolation, and recovery is an essential requirement of any space mission design. Several spacecraft components, especially sensors, are prone to performance deviation due to intrinsic physical effects. For that reason, innovative approaches for the treatment of faults in onboard sensors are necessary.

This work introduces the concept of agent-based fault detection and recovery for sensors used in satellite attitude determination and control. Its focuses on the implementation of an algorithm for addressing linear drift bias in gyroscopes. The algorithm was implemented using an agent-based architecture that can be integrated into the satellite's onboard software.

Numerical simulations were carried out to show the effectiveness of this scheme in satellite's operations. The proposed algorithm showed a reduction of up to 50% in the stabilization time for the detumbling maneuver, and also an improvement in the pointing accuracy of up to 20% when it was applied in precise payload pointing procedures.

The relevance of this contribution is its added value for optimizing the launch and early operation of small satellite missions, as well as, an enabler for innovative satellite functions, for instance, optical downlink communication.

1. Introduction

Space missions involving the use of small satellites are becoming more sophisticated. Besides technology demonstration, there is an increasing number of earth observation missions requiring more demanding capabilities [1]. Higher pointing accuracy is one of the most challenging functions to improve, especially in small satellites. For that purpose, a more precise and reliable attitude and orbit control subsystem (AOCS) is needed; One that enables autonomous fault detection and recovery features.

Two main approaches are typically used for fault detection, isolation and recovery purposes: Hardware redundancy and analytical redundancy. Analytical redundancy is more cost-effective and thus preferred over hardware redundancy in industrial applications, where physical redundancy is highly constraint [2].

Within the analytical redundancy, the model-based methods have been widely used in safety critical applications requiring fault-tolerant control (FTC) [3]. Examples of such uses are found in chemical processes [4] and automobile industry [5]. However, data-driven methods are taking over model-based methods due to their increased performance and implementation flexibility [6]. A combination of both hardware and analytical schemes can benefit the efficiency of FDIR performance.

Fault detection, isolation and recovery methods are divided into fault diagnostics (FDI), and fault isolation and recovery (FIR). FDI includes fault detection and identification, while FIR preserves systems integrity by isolating faulty subsystems and executing recovery procedures when needed [7]. Implementation of such algorithms is an important aspect to consider during the space mission design process, since more the capabilities added, the more complexity it has to be managed during the implementation phase.

In this work, an algorithm to address fault detection and recovery of drift bias in AOCS sensors is described using a novel agent-based approach to mitigate implementation complexity and enabling configuration flexibility.

Alternative methods, for instance, underactuated control, have been proposed to deal with failures in spacecraft [8]. However, the biggest challenge with existing algorithms is their high sensitivity to disturbances, which have been addressed by proposing nonlinear H-infinity control algorithms. Furthermore, these controllers require precise sensor measurements to become more efficient. That is an additional motivation

* Corresponding author.
E-mail addresses: j.carvajalgodinez@tudelft.nl (J. Carvajal-Godinez), j.guo@tudelft.nl (J. Guo), E.K.A.Gill@tudelft.nl (E. Gill).

http://dx.doi.org/10.1016/j.actaastro.2017.07.001
Received 7 November 2016; Received in revised form 19 June 2017; Accepted 4 July 2017
Available online 6 July 2017

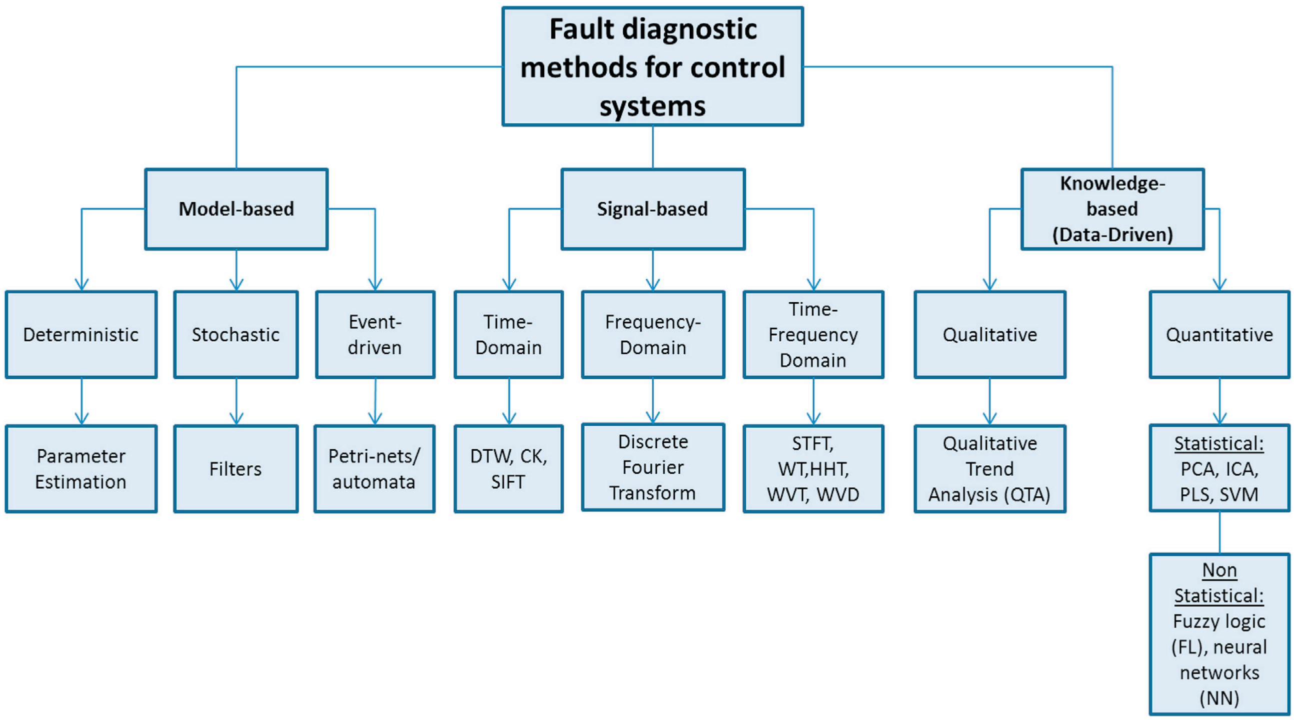

Fig. 1. Fault diagnostic and recovery methods for control systems.

to improve sensor performance in AOCS subsystems.

This paper has two main contributions to the aerospace field. First, is the implementation of a hybrid (model/data-driven) fault detection and recovery algorithm for angular rate gyroscopes. Missions with sensor redundancy in their attitude determination and control subsystem, for instance BIROS [9], can take advantage of the dynamic features proposed by agent-based algorithms to improve its mission performance, compared to the traditional static estimation of drift bias that is commonly implemented in small satellites. Second, is the flexibility that multi-agent systems provides to the design of fault detection and recovery schemes. These two aspects can increase mission's reliability and performance for enabling a framework to develop more autonomous AOCS software.

The structure of the paper will be as follows: Chapter 2 summarizes the current state of the art for fault detection, isolation, and recovery methods in sensors and actuators, and it makes a description of the problem addressed by this work. Chapter 3 describes the proposed Agent-based algorithm for fault detection and recovery and its architecture implementation. Chapter 4 presents and discuss practical scenarios for small satellite missions where this contribution shows a practical value. Finally, Chapter 5 draws conclusions and future directions for this research.

2. Problem formulation

2.1. FDIR methods - state of the art

This section presents and discusses the latest reported methods for failure detection, isolation and recovery (FDIR) applied to sensors and actuators in control systems. The main objective is to support the selection of a hybrid approach for the fault detection and recovery algorithm developed in Chapter 3. According to the latest FDIR surveys [2,7,10] there are four main categories of fault diagnostic and recovery methods used in control system: model-based, signal-based, knowledge-based and hybrid.

Model-based methods require breaking down the systems into functions and processes that are formulated mathematically. A fault diagnostic observer checks the consistency between the physical measurements and the predicted output from the system model. The observer can recognize deviations from the expected behavior and correct them by updating systems parameters.

In signal-based methods, instead of using a specific input/output model, an observer extracts symptoms from the output measurements, and it compares them with a set of predefined fault signatures. Signal-based methods assume the input to be a reliable signal, and the observer verifies its consistency along the time. Signal-based diagnostic methods are classified into three subgroups: time-domain, frequency domain, and time-frequency combined.

For continuous and dynamic processes, the time domain is preferred over the others. There are several applications in mechanical and electrical systems where time-domain methods are used for fault diagnostics. For instance, a statistical time-domain algorithm focuses on analyzing signal covariance to find out faulty signatures [11]. Another signal-based algorithm used for actuators is Dynamic Time Warping (DTW), which detects periodic impulse responses caused by faulty electromechanical components inside the actuator [12].

Within the frequency domain algorithms, Fourier Discrete Transformation (FDT) is the preferred. It is widely used in vibration analysis, where faults are detected by measuring shifts on frequency spectrum [13]. Combining time and frequency domain method is feasible for signal-based fault detection and isolation. The literature also reports the use of short time Fourier Transform (STFT) and Wavelet Transforms (WT) for motor eccentricity fault detection and isolation as described in Ref. [14]. The main concern of combining time and frequency approaches is their high computational cost, which might not be suitable for resource constraint computers inside of small satellites.

The third FDIR category is the knowledge-based, which consist of two groups: quantitative and qualitative. The key characteristic of knowledge-based methods is that they are mainly data-driven. They include the use of artificial intelligence, expert systems, machine learning, pattern recognition and its variants [7]. From the data-driven perspective, the FDIR problem can be divided into three phases: fault classification, regression, and reconfiguration. Data-driven quantitative algorithms are subsequently divided into statistical, non-statistical and