Preface

The increasing complexity of space vehicles such as satellites, and the cost reduction measures that have affected satellite operators are increasingly driving the need for more autonomy in satellite diagnostics and control systems. Current methods for detecting and correcting anomalies onboard the spacecraft as well as on the ground are primarily manual and labor intensive, and therefore, tend to be slow. Operators inspect telemetry data to determine the current satellite health. They use various statistical techniques and models, but the analysis and evaluation of the large volume of data still require extensive human intervention and expertise that is prone to error. Furthermore, for spacecraft and most of these satellites, there can be potentially undue long delays in round-trip communications between the ground station and the satellite. In this context, it is desirable to have onboard fault-diagnosis system that is capable of detecting, isolating, identifying or classifying faults in the system without the involvement and intervention of operators. Toward this end, the principle goal here is to improve the efficiency, accuracy, and reliability of the trend analysis and diagnostics techniques through utilization of intelligent-based and hybrid-based methodologies.

It is a well-recognized fact that an automated satellite health monitoring and fault diagnosis system using advanced decision-support systems is the need of today’s satellite ground support system. A system that can generate an early-warning to the operator is well suited to satellite ground operations where the operators are already overloaded with satellite command and control tasks. Due to recent advances in computing technologies, health monitoring and fault diagnosis schemes for satellites can be automated using advanced decision-support systems such as rule-based expert systems and artificial intelligence (AI)-based methodologies. Soft computing based on artificial neural-networks is witnessing an increasing use in such activities.

Toward this end, in this work we have developed, analyzed, and implemented novel techniques to accurately monitor the telemetry data of the satellite’s ACS system to pinpoint potential causes of actuator anomalies and failures and to facilitate and optimize the operator resources to critical events for troubleshooting problems. Different approaches have been investigated and developed for accurately predicting actuator failures based on detection of abnormal and/or subtle deviations of the actuators from their normal range in key variables/feature points. We believe this additional diagnostic capability combined with autonomous fault detection, diagnosis,
and recovery technologies would be beneficial for existing and future-planned space missions as well as for increasing the expected life span of current satellites or for enhancing the future designs.

Conventionally, fault-tolerant control systems are achieved and ensured through hardware redundancy, that is, by including redundant actuators and sensors in the system. The control and measurement channels are generally made duplicated or triplicated in hardware. The main disadvantage of physical redundancy is the additional cost and the corresponding increase in complexity of operation. Moreover, the weight of the system and the maintenance requirements are subsequently increased. Consequently, analytical redundancy approach, which makes use of the mathematical model of the system and relationships between sensor outputs and actuator inputs, has been proposed and are increasingly being employed in complex control systems.

In a large-scale complex system such as a satellite or a space vehicle not every process or subsystem can be mathematically and accurately modeled. Therefore, we will look at computationally intelligent architectures as alternative means for representing the system. Neural networks have a great deal of potential in this area since these networks can generate input/output mappings that can approximate any nonlinear function with any desired degree of accuracy under certain mild assumptions. Additionally, neural networks have proven to be excellent pattern characterizers for both static and dynamically behaving patterns. One aspect of this work will focus on developing neural networks methods for extracting and characterizing such behavior patterns. A formal methodology is developed to allow the space vehicle to make a wide variety of decisions and is capable of planning and executing diagnosis activities autonomously.

There are essentially three distinct fault diagnosis approaches that one could investigate:

- Techniques that use physics-based model of the satellite and use the traditional techniques from the estimation and control domain to tackle the problem,
- Techniques that use artificial neural networks (ANN), fuzzy logic, and genetic and evolutionary algorithms for model development and use those models along with other intelligent networks for fault detection and isolation purposes, and
- Finally, there is a possibility to use a combination of the above two methodologies as a hybrid method for model development as well as fault diagnosis logic.

Building on methods presently available in several fields including system identification, robust and adaptive control, computational intelligence, and system health monitoring, novel and innovative techniques have been investigated in this work by developing new capabilities and by relaxing/removing the limitations of the current state-of-the-art technology in fault diagnosis as they relate to nonlinear systems. This interest is motivated by the fact that most available fault diagnosis techniques lack the capability to handle incomplete and varying knowledge concerning fault modes. The classical methods that consider such knowledge are inflexible, and hence not suitable for complex systems such as satellites and spacecraft.
that are considered here. The approach proposed and the interest pursued here are in integration of the analytical techniques with the computational intelligence methodologies. By taking advantage of the efficient data-processing capabilities of model-based approaches, and the capability of intelligent systems in handling incomplete, less-formalized and even uncertain knowledge, an integrated and a hybrid approach is envisaged to produce more flexible and practical solutions. The proposed approach consists of hierarchical and distributed fault diagnosis systems whereby for each subsystem or component of our complex system, a separate diagnoser module can be designed, tested and validated. In this way, the fault analysis is enabled through insight into the physical and operational characteristics of the system. The intelligent and high level-based methods are then capable of organizing results from all fault diagnosis modules in a role of a supervisory control. The proposed intelligence-based techniques will be used both locally and globally.

This monograph is organized as follows. In Chapter 1, we will provide an overview of the fault diagnosis literature in general and fault detection methodologies in particular. A more formal presentation of the fault diagnosis problem, further details on the issues involved, and some of the methodologies developed for fault diagnosis in the literature especially for fault isolation and identification tasks are reviewed. Chapter 2 formally defines the fault diagnosis problem in nonlinear systems and presents a comprehensive literature review and analysis of different approaches to fault detection, isolation, and identification (FDII) of both linear and nonlinear systems. Both model-based and computational intelligence-based approaches to fault diagnosis have been extensively reviewed and analyzed, and a number of well-known methodologies within each framework are further demonstrated and their respective pros and cons are cited. Chapter 3 demonstrates both the series-parallel and the robust parallel structures of the hybrid nonlinear FDII methodology under full-state measurement assumption, which is the core contribution of this monograph. Chapter 3 also introduces a specific formulation of the problem of FDII in nonlinear systems as a nonlinear parameter estimation problem using the notion of parameterized fault models (PFMs). A short survey of various model-based and computational intelligence-based nonlinear parameter estimation techniques is also performed in this chapter. In Chapter 4, first the theory of state estimation or filtering has been comprehensively reviewed in order to design and develop a fault tolerant state estimator that enables FDII under partial-state measurement conditions. A specific adaptive neural state estimator (NSE) is then designed and its integration with the proposed hybrid FDII schemes are described in this chapter. Chapter 5 explains the spacecraft attitude control system and reaction wheel actuators to which the proposed fault diagnosis algorithms are applied. Simulation results demonstrating the effectiveness and validating the properties (such as robustness) of the proposed FDII algorithms have also been proposed in this chapter. Finally, concluding remarks and future research directions are included in Chapter 6.

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