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A pulsed plasma thruster fault detection and isolation strategy for formation flying of satellites[☆]

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ABSTRACT

The main objective of this paper is to develop a dynamic neural network-based fault detection and isolation (FDI) scheme for pulsed plasma thrusters (PPTs) that are employed in the attitude control subsystem (ACS) of satellites tasked to perform formation flying (FF) missions. A hierarchical methodology is proposed that consists of three fault detection and isolation (FDI) approaches, namely (i) a "low-level" FDI scheme, (ii) a "high-level" FDI scheme, and (iii) an "integrated" FDI scheme. Based on the data from the electrical circuit of the PPTs, the proposed "low-level" FDI scheme can detect and isolate faults in the PPT actuators with a good level of accuracy, however the precision level is poor and below expectations with the misclassification rates as expressed by False Healthy and False Faulty parameters being too high. The proposed "high-level" FDI scheme utilizes data from the relative attitudes of the FF mission. This scheme has good detection capabilities, however its isolation capabilities are not adequate. Finally, the proposed "integrated" FDI scheme takes advantage of the strengths of each of the above two schemes while reducing their individual weaknesses. The results demonstrate a high level of accuracy (99.79%) and precision (99.94%) with a misclassification rates that are quite negligible (less than 1%). Furthermore, the proposed "integrated" FDI scheme provides additional and interesting information related to the effects of faults in the thrust production levels that would not have been available from simply using the low or the high level schemes alone.

1. Introduction

New generation of future space missions are being envisaged as groups of coordinated small-size spacecraft (micro-satellites) that can perform the same mission that large spacecraft can achieve but with much improved performance, reliability, fault tolerance, and reduced mission cost [1–6]. One type of coordinated spacecraft mission is known as the formation flying maneuvers. Examples of formation flying missions for near-Earth and deep space environments are presented in [7–11]. Malfunctions of sensors or actuators in the attitude and orbital control subsystem (AOCS) of the spacecraft can affect the performance of the entire precision formation flight. Early detection of malfunctions or faults is a mandatory requirement for safety critical systems. Fault detection and isolation (FDI) schemes for the attitude and orbital control subsystem of spacecraft have been developed in the past two decades. The literature on FDI for spacecraft has considered faulty components such as sensors and actuators [12–16].

The actuators that are most commonly used for large attitude maneuvers are the reaction wheels and control moment gyroscopes. Pulsed plasma thrusters (PPTs) are an alternative type of actuators that are mostly utilized for small satellites. Unfortunately, faults that produce undesirable variations in the amount of force that is generated by the PPTs are not physically measurable and observable. Therefore, the development of a FDI system for detecting and isolating faults in PPT thrusters is a challenging problem.

The FDI techniques in the literature maybe divided into history-based and model-based categories. Neural networks are among the well-known history-based techniques that are capable of learning models of nonlinear systems from past input–output data. In the case of spacecraft attitude control subsystem, a number of neural network-based FDI schemes have been developed and investigated in the literature [17–21]. In this paper, a neural network-based FDI scheme that is capable of detecting and isolating faults in the PPT thrusters used in the formation flying of satellites is developed. The proposed FDI system uses a special multilayer perceptron network that is known as the dynamic neural network (DNN) [22–24].

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A formation flight is defined as "two or more spacecraft that use an active control scheme to maintain the relative positions of the spacecraft" [25]. In this work, we consider a typical formation of three spacecraft in a near-Earth orbit for simulation experimentations. In formation flight of spacecraft at least two vehicles use an active control scheme to maintain their relative positions [26]. An alternative definition is provided in [27] where formation flying is defined as a set of more than one spacecraft in which any of the spacecraft dynamic states are coupled through a common control law. This definition is complemented with two conditions: (i) at least one spacecraft in the formation must track a desired state profile relative to another spacecraft, and (ii) the associated control law must at minimum depend upon the state of the other spacecraft.

The above active control scheme or common control law can be understood as the formation flying control. There are five different formation flying control architectures that are introduced in the literature [25,27]. The leader/follower architecture is among the most common formation flying configurations. For this reason the control architecture considered and implemented in this work will be for the leader/follower scheme.

For the sake of clarity, let us now explicitly state the main contributions of this work.

- A novel fault detection and isolation scheme for pulsed plasma thrusters (PPTs) used in the attitude control subsystem of the formation flying of satellites is proposed by constructing four dynamic neural networks (DNNs). The proposed FDI scheme is capable of successfully detecting and isolating three classes of commonly occurring faults in PPT actuators that can adversely affect precision of the formation flying attitudes.
- Notwithstanding the fact that the literature contains a large body of work on various fault diagnostic systems for common attitude control subsystem actuators (such as reaction wheels, control moment gyroscopes, and magentorquers), development of fault diagnostic systems for pulsed plasma thrusters has not been addressed. Given the fact that the forces that are generated by the PPT actuators cannot be physically measured, and given the lack of high fidelity, precise, and simple mathematical models for PPTs, development of a fault diagnostic scheme for PPTs is not a trivial task. In this work, it is demonstrated that the proposed neural network-based FDI scheme is not a complicated scheme and is indeed a reliable tool for detecting and isolating faulty PPTs.
- The results obtained through extensive numerical simulation scenarios show a high level of accuracy (99.79%) and precision (99.94%) with very low and negligible misclassification rates corresponding to the False Healthy (0.03%) and the False Faulty (0.61%) metrics. The applicability of the DNN methodology for solving a fault diagnosis problem in a highly complex nonlinear system such as the formation flying systems was successfully demonstrated.
- Formation flying missions are gaining more attention and interest by the space industry and academia due to a number of attractive advantages and benefits that are offered by these systems. A significant reduction in the amount of hours that could potentially be spent by the ground station personal can be achieved by implementing computationally intelligent-based methodologies that are proposed and developed in this paper. Therefore, the operational mission cost can be significantly reduced and the reliability and performance of the overall formation mission can be significantly improved.

The organization of the remainder of the paper is as follows. In Section 2, the general model for the satellite's attitude control subsystem and the dynamical model of the formation flight system are briefly described. In Section 3, the dynamics of the PPT's electromechanical system that are used to simulate the satellite's attitude maneuvers under normal and abnormal conditions are presented. In Section 4, a "low-level" dynamic neural network-based fault detection and isolation scheme for the PPT of a satellite is developed. An evaluation analysis of this FDI scheme is also presented. In Section 5, a "high-level" dynamic neural network-based fault detection and isolation scheme at the formation-level is developed and the simulation results are discussed and compared with the results of the "low-level" FDI schemes. In Section 6, the strengths and weaknesses of both FDI schemes are discussed and an "integrated" FDI scheme capable of taking advantage of the strengths of each scheme is proposed and evaluated through extensive simulation studies. Conclusions are presented in Section 7.

2. Formation flying and satellite attitude control subsystem

Without loss of generality and for illustrative purposes, consider the formation flying of system where the leader/follower architecture is composed of three satellites. One spacecraft is designated as the "Leader" (s/c_l) and the other two spacecraft are the "Followers" (s/c_{f1}) and (s/c_{f2}). The followers receive the attitude coordinates of the leader and according to a previously defined reference, s/c_{f1} and s/c_{f2} correct their own attitudes. From the attitude control point of view s/c_l is considered as a single spacecraft. Therefore, the attitude control subsystem (ACS) of the spacecraft s/c_l is operating with the absolute attitude measurements. On the other hand, the s/c_{f1} and s/c_{f2} correct their attitudes relative to the leader's attitude and as result the ACS of s/c_{f1} and s/c_{f2} operate with relative attitude measurements (i.e. relative to the leader's attitude).

The equations of motion describing the dynamics of a single spacecraft are given by the following nonlinear state space representation:

$$\begin{aligned} \dot{\vec{x}} &= f(\vec{x}) + g(\vec{x})\vec{u} \\ \vec{y} &= \vec{x} \end{aligned} \tag{1}$$

where the state, the control, and the output vectors are denoted by $\vec{x} = [\omega_x, \omega_y, \omega_z, q_0, q_1, q_2, q_3]^{\mathrm{T}}$, $\vec{u} = [T_x, T_y, T_z]^{\mathrm{T}}$ and $\vec{y} = [\omega_x, \omega_y, \omega_z, q_0, q_1, q_2, q_3]^{\mathrm{T}}$, respectively. The elements of the state vector ω_x, ω_y, ω_z are the angular velocity of the CoM of the spacecraft with respect to the x-axis, y-axis and z-axis, respectively, and q_0, q_1, q_2, q_3 represent the quaternions [28]. The elements of the control vector T_x, T_y, T_z are the total torques that is applied about the x-, y- and z-axes of the spacecraft, respectively. Eq. (1) is used to represent the dynamics and the kinematics of each spacecraft in the formation flying system.

Attitude controllers receive from ACS sensors the spacecraft's absolute (or relative) attitude measurements and then utilize them to calculate the deviations from the desired absolute (or relative) angles. This would be translated into commands for the actuators to provide the required torques to perform absolute (or relative) attitude correction actions. Due to its simplicity and robustness, it was decided to implement a Quaternion Error Vector Command Law [29] for all the spacecraft in the formation. The only difference between the leader s/c_l controller and the follower s/c_{f1} and s/c_{f2} controllers is that in the case of the followers, the measurements (angles and angular velocities) are relative to the s/c_l attitude.

In the formation flying mission, the three spacecraft (s/c_l, s/c_{f1} and s/c_{f2}) need magnetometer and gyroscope sensors. Due to the formation flying attitude control requirements, s/c_{f1} and s/c_{f2} need the s/c_l attitude, therefore communication equipments such as autonomous formation flying (AFF) sensors [30] are also required. To provide the commanded torques, the three spacecraft are