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Actuator fault detection and isolation: An optimised parity space approach

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ABSTRACT

The use of an optimised parity space approach for actuator fault detection and isolation (FDI) is explored. The parity space spans all the parity relations that quantify the analytical redundancies available between the sensor outputs and the actuator inputs of a system. A transformation matrix is then optimised to transform these parity relations into residuals that are especially sensitive to specific actuator faults. Actuator faults cause the variance of parity space residuals to increase. A cumulative summation procedure is used to determine when residual variance has changed sufficiently to indicate a locked-in-place actuator fault. A pseudoinverse actuator estimation scheme is used to extract the actuator deflections from the parity relations. It is found that the optimisation of the parity space approach introduces the advantage of added design freedom to the fault detection algorithm. The approach is applied to the identification of faulty aircraft control surface actuators that remain locked-in-place during flight and is successfully tested both in simulation and practical flight.

1. Background

With increased technological advancement over the past century, our reliance on systems that govern our daily lives has become greater than ever before. The complexity of these systems necessitates improved reliability of their control schemes. It is clear that a structure of fault detection is paramount in the pursuit of safety, reliability and performance. Automated systems that totally or partially rely on themselves to achieve these three objectives are clearly emerging. Unmanned Aerial Vehicles (UAVs) are applicable automated systems that have increasingly been used since the 1990s for important tasks in several different industries (Ducard, 2009).

Because of the large economic benefit UAVs have, it becomes apparent that the safety and reliability of these UAVs are vital. Several different schemes are being used to meet these goals. Robust control design is frequently used but typically compromises on performance (Ackermann, Bartlett, Kaesbauer, Sienel, & Steinhauser, 1993; Zhou & Doyle, 1998). Fault tolerant control (FTC) systems overcome the need to compromise on performance, typically by detecting faults and then adapting control architectures (in some optimal way) to the fault that has occurred (Maki, Jiang, & Hagino, 2004; Wise et al., 1999). The aim of fault tolerance in a UAV is to prevent component or subsystem faults from developing into serious system failure, hence increasing the safe operational availability of the system (Zhang & Jiang, 2008).

In a typical aircraft the pilot or control system can manipulate a set of input mechanisms. These mechanisms, such as the propulsion system and control surfaces, are controlled to create moments and forces that ultimately change the states of the aircraft in some desired manner. The control surfaces are also commonly referred to as actuators.

Control allocation and re-allocation (Basson, 2010) are important processes in a typical FTC scheme. A faulty actuator degrades the achievable combination of moments and forces that can be created by the set of actuators, but the control re-allocation process mixes the available actuators in some optimal way in order to attempt to overcome this problem. However, for most control allocation schemes to work, the following must be known: if a fault has indeed occurred; what type of fault occurred; the magnitude of the fault; and which actuators are defective (Ducard, 2009).

For an effective control allocation process a reliable actuator fault detection and isolation (FDI) system must be in place to supply this required information. Aircraft can use several costly sensors directly attached to the control surfaces to conduct the FDI process by means of a voting scheme (Parker, 1998). It is becoming a common practice to use analytical redundancy to supplement some of the sensors in achieving FDI and so to reduce the required costs and improve the overall reliability of FDI (Patton, 1991). The

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topic of this research focuses on fault detection and isolation of locked-in-place faults through the use of an optimised parity space approach.

The FDI scheme is run on board the aircraft and in real time. In most systems, the fault detection algorithm is running continuously, while the isolation task is activated only upon the detection of the fault (Gertler, 1998). There are also two primary families of FDI systems, namely active and passive FDI systems. Active FDI will constantly monitor the system while artificially exciting the UAV (Cieslak, Henry, & Zolghadri, 2008; Maki et al., 2004; Niemann, 2005, 2006; Poulsen & Niemann, 2008) through the aircraft's actuators. This method decreases the time it takes to detect a fault and can also guarantee fault detection in a set amount of time (Busch & Peddle, 2014). The disadvantages of active fault detection include that more energy is used to excite the actuators, the actuators wear out faster due to more use, and some level of performance is lost. The second family is passive FDI systems, which also constantly monitor the health of the actuators, but do not artificially excite the actuators to assist the FDI process (Hearns, Grimble, & Johnson, 1998). The advantages of passive FDI are therefore that the FDI scheme does not (under nominal conditions) influence flight performance, less energy is consumed by the actuators and less actuator wear-and-tear results. It does not however guarantee that a fault will be detected in a given time frame. The parity space method can be used as either an active or passive FDI technique.

Several FTC methods exist, but for the purpose of this research it is assumed that control re-allocation coupled with an FDI module will be the default architecture. An in-depth analysis of the topic is beyond the scope of this paper. For a comprehensive list of different FTC methods available, consult Zhang and Jiang (2008).

There are also several FDI methods available. These FDI methods can depend on a model based approach or a data based approach (Zhang & Jiang, 2008). For the purposes of this research a mathematical model of the aircraft was available. As such a model based approach was followed. The model based approaches can further be classified according to their outcomes as qualitative or quantitative method. A qualitative method can use fuzzy logic or other decision processes to give a measure of fault quality, for example “the left rudder is stuck at a high deflection angle”. The quantitative methods apply numerical values to their decisions such as “the right aileron is stuck at -3°”. The most control re-allocation system requires quantitative information to operate and therefore a quantitative method for FDI is an obvious choice.

Techniques that address the creation of residuals for quantitative, model based FDI include (Ducard, 2009)

- *State estimation techniques*: A fault usually changes the expected state of a system in an additive way. State estimation techniques use the innovations (measurement residual) of the estimators as a means to quantify the discrepancy between the expected behaviour of the system and the observed behaviour. Most faults can be classified as additive. This method is therefore quite attractive. Simple observer based approaches (Wang & Lum, 2007) and more formal Kalman filter (KF) based (Eide & Maybeck, 1996) approaches are examples of this method.
- *Parameter estimation techniques* (Åsröm & Eykhoff, 1971): Parameter estimation is an intuitive approach for determining multiplicative faults. The dynamic parameters of the system are estimated and compared with the nominal values of a fault-free system model. Parameter estimation is more reliable than analytical redundancy methods, but it requires more computational power and external excitation. Recursive least squares (Ward, Barron, Carley, & Curtis, 1994) and regression analysis (Åsröm & Eykhoff, 1971) are two parameter estimation techniques used for FDI.
- *Parity space techniques* (Zhang & Jiang, 2008): The parity space relations are the relationships found between the inputs and outputs of a system and are used as residuals for the FDI system. These relations are obtained from the system's rearranged mathematical model subject to a linear transformation. The design freedom obtained through the transformation can be used to decouple disturbances and improve fault isolation. The input–output based (Gertler, 1998) approach and the state space based (Chow & Willsky, 1984) approach are two parity space FDI methods.

Once residuals are created by one of the methods proposed above an appropriate decision process must accompany the FDI to generate a reliable fault decision.

1.1. Outline

The paper starts with a brief introduction and literature review regarding FDI and fault tolerant control design. It guides the reader to discovering where parity space fits into the scope of FDI techniques. The introduction is followed by a section stipulating the goals of the research, whereafter the UAV used in this research is described. In Section 4 the parity space approach is defined in detail and the possibility of optimisation is pointed out. A basic optimisation technique is used as the first step in testing this hypothesis after which a CUSUM procedure is outlined as the fault decision process. In Section 5 the optimised parity space technique's FDI performance is tested in simulation as well as practical flight tests. Discussions and conclusions are detailed in Section 6.

2. Goals

Both the input–output and state space methods, which fall under the parity space based approach, are covered in Gertler (1998). The input–output based method is an excellent FDI development method, but problems arise when more faults can occur than the number of useful detection sensors. This is the case with the aircraft which is used to support this research at Stellenbosch University, known as the Meraka Modular UAV. The opportunity therefore arose to determine if the state space based method can be used to allow for more design freedom by applying optimisation techniques.

The goal of this research can be expressed as delivering reliable information regarding the current state of the aircraft actuators, without the use of sensors directly attached to the actuators. The solution process may be summarised as

- Creating an actuator fault detection and isolation system using the state space parity space approach.
- Optimising the primary residuals for actuator FDI.
- Implementing an appropriate fault decision algorithm.
- Testing FDI performance in both a simulation environment and an actual test flight environment.

Project funds were secured to test the project scope on the Meraka Modular UAV. The scope of the project was limited to isolate locked-in-place faults. This application helped to determine the basic characteristic behavior and viability of the proposed method.

3. The Meraka Modular UAV

A non-linear six degrees of freedom mathematical model was created for the Meraka Modular UAV. The creation of this model is