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Qualitative event-based diagnosis applied to a spacecraft electrical power distribution system

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ABSTRACT

Quick, robust fault diagnosis is critical to ensuring safe operation of complex engineering systems. A fault detection, isolation, and identification framework is developed for three separate diagnosis algorithms: the first using global model; the second using minimal submodels, which allows the approach to scale easily; and the third using both the global model and minimal submodels, combining the strengths of the first two. The diagnosis framework is applied to the Advanced Diagnostics and Prognostics Testbed that functionally represents spacecraft electrical power distribution systems. The practical implementation of these algorithms is described, and their diagnosis performance using real data is compared.

1. Introduction

Fault diagnosis plays an essential role in ensuring system safety in many application domains, from industrial power plants to aerospace vehicles. When a fault occurs in a system, diagnosis software must be able to quickly detect the presence of the fault, isolate the true fault among many potential fault candidates, and identify the fault magnitude (Chen & Patton, 1999; Gertler, 1998; Isermann, 1997; Patton, Frank, & Clark, 2000). With this information, automated mitigation and recovery actions can be taken. Proper recovery actions enable successful continued operation and prevention of catastrophic consequences, both of which lead to cost savings (Goupil, 2010, 2011).

In this paper, a model-based diagnosis approach for the Advanced Diagnostics and Prognostics Testbed (ADAPT), an electrical power distribution system that is representative of those on spacecrafts, is developed. ADAPT serves as a testbed through which faults can be injected to evaluate diagnostic and prognostic algorithms (Poll et al., 2007a). Located at NASA Ames Research Center, ADAPT has been established as a diagnostic benchmark system through the industrial track of the International Diagnostic Competition (DXC) (Kurtoglu et al., 2009; Sweet, Feldman, Narasimhan, Daigle, & Poll, 2013). Within the DXC, specific diagnostic problems are defined for ADAPT, and competing algorithms are evaluated using real experimental data obtained from the ADAPT hardware. Diagnostic algorithms must deal with a variety of real-world issues in order to be successful. In particular, this paper is focused on diagnosing faults on a subset of ADAPT, called the ADAPT-Lite. The application context is that of an unmanned aircraft system, and the diagnosis must be used to provide mission abort/continue commands (Kurtoglu et al., 2009). In order to do this, faults must be correctly detected (i.e., determine if a fault is present in the system), isolated (i.e., determine which fault has occurred), and identified (i.e., estimate the parameters that define the fault behavior), under the single fault assumption. Although solutions in this work are specifically developed for ADAPT, the approach is model-based and therefore can be applied to different systems given suitable models.

The model-based diagnosis approach developed in this work is rooted in a qualitative fault isolation framework that is based on the analysis of residual signals, where residuals are computed as the difference between observed and predicted system variables (Mosterman & Biswas, 1999). Faults in the system are modeled as changes in the value of the system parameters (Mosterman & Biswas, 1999) and as changes in component modes (Daigle, Koutsoukos, & Biswas, 2009). Faults cause discrepancies in observed behavior and model-predicted behavior, and thus manifest as deviations in the residual signals. Fault detection involves statistical testing of the residuals. The transients of residual deviations are abstracted qualitatively and compared to predicted fault transients to enable quick fault isolation. Both the qualitative change in the residual signal, expressed as + and − values in

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magnitude and slope, and the temporal ordering of these transients as they manifest in the residuals, are used as diagnostic information, establishing an event-based qualitative fault isolation framework (Daigle et al., 2009).

Predicted values of system outputs are computed by using models of the system, which can be either a global model of the system or local submodels. Structural model decomposition methods can be used to systematically compute the submodels. The use of local submodels leads to increased scalability of the diagnosis algorithm (Bregon et al., 2014; Thompson, 1994) and increased diagnosability. They have been successfully used for fault diagnosis in industrial (Arogeti, Wang, Low, & Yu, 2012) and aerospace applications (Fravolini & Campa, 2009). The main idea is to take advantage of the analytical redundancy provided by the sensors and the model to derive minimal submodels that provide additional information useful for diagnosis. In particular, this paper uses a structural model decomposition approach based upon Possible Conflicts (PCs) (Pulido & Alonso-González, 2004), which is a structural model decomposition technique equivalent to Analytical Redundancy Relations (ARRs) (Arogeti et al., 2012, 2010). PCs are computed off-line as the minimal subsets of the global model constraints that produce inconsistencies when faults occur. Residuals may be computed using PCs, and residual deviations analyzed following the qualitative fault isolation framework (Bregon, Biswas, & Pulido, 2012; Daigle et al., 2009; Mosterman & Biswas, 1999). Then, quantitative fault identification can be carried out by using minimal local submodels for parameter estimation (Bregon et al., 2012).

The contributions of this work are as follows. First, a novel model-based diagnosis framework is developed that addresses fault detection, isolation, and identification. It combines techniques from qualitative fault isolation and structural model decomposition. Specifically, structural model decomposition is used as an underlying technique to automatically determine the sets of submodels for each diagnosis task. From this framework, several diagnoser designs can be derived using different sets of models and submodels. It is shown that two previous algorithms, QED (Qualitative Event-based Diagnosis) and QED-PC (QED with Possible Conflicts) (Daigle, Bregon, & Roychoudhury, 2012) can be formulated as specific instantiations of this framework, where QED uses a global system model, and QED-PC uses minimal local submodels. A new algorithm, QED-PC++, that uses both the global model and the minimal local submodels, is formulated, and it is shown how it combines the strengths of QED and QED-PC. The three algorithms are implemented as diagnostic solutions for the ADAPT case study, which includes the development of models of ADAPT suitable for diagnosis, the integration of heuristic fault isolation rules to improve fault isolation performance, and novel fault identification techniques. Using a large, comprehensive set of experimental data from the ADAPT hardware, the three algorithms are applied and their performance is compared. By analyzing the set of experimental results, their limitations are discovered, and possible future improvements and extensions are suggested.

The paper is organized as follows. Section 2 describes the ADAPT case study. Section 3 overviews the diagnosis approach. Section 4 provides the system model and describes the structural model decomposition approach. Section 5 describes fault detection and Section 6 describes symbol generation. Section 7 discusses fault isolation, and Section 8 describes fault identification. Section 9 covers decision-making. Section 10 presents the experimental results and discusses lessons learned. Section 11 describes related work, and Section 12 concludes the paper.

2. The Advanced Diagnostics and Prognostics Testbed

The Advanced Diagnostics and Prognostics Testbed is an electrical power distribution system that is representative of those on spacecraft, and has been established as a diagnostic benchmark system through the International Diagnostic competition (Poll et al., 2007b). As mentioned in the previous section, this work focuses on a subset of ADAPT, called ADAPT-Lite, which has been used to define Diagnostic Problem I of the industrial track of the DXC (Kurtoglu et al., 2009; Sweet et al., 2013), in which the ADAPT-Lite hardware is used to emulate the operation of an electrical power system aboard an Unmanned Aircraft System (UAS).

A system schematic for ADAPT-Lite is given in Fig. 1. A battery (BAT2) supplies electrical power to several loads, transmitted through several circuit breakers (CB236, CB262, CB266, and CB280), relays (EY244, EY260, EY281, EY272, and EY275), and an inverter (INV2) that converts dc to ac power. ADAPT-Lite has one dc load (DC485) and two ac loads (AC483 and FAN416). There are sensors throughout the system to report electrical voltage (names beginning with "E"), electrical current ("IT"), and the positions of relays and circuit breakers ("ESH" and "ISH", respectively). There is one sensor to report the operating state of a load (fan speed, ST516) and another to report the battery temperature (TE228).

A diagnostic algorithm is used to inform the operator if faults have occurred, and if so, whether the fault requires aborting the mission and landing the UAS. Given the time-stamped vectors of system inputs $\mathbf{u}(t)$ and outputs $\mathbf{y}(t)$, the goal of the diagnosis algorithm is to detect the fault, isolate the faulty component and its fault mode, identify the fault magnitude, and then generate an *abort* command if necessary by $t=4$ min into the mission. The necessity of an abort depends on the fault type, and, in some cases, on the fault magnitude, thus, this diagnostic problem requires the diagnostic algorithm to perform not only fault detection and isolation, but also fault identification.

Table 1 summarizes the abort recommendation for each fault mode in ADAPT-Lite. A command to abort should be given for any fault that results in a loss of power to the three loads, i.e., faults in any of the circuit breakers or relays, a failure in the inverter, and failures in the loads themselves. An overspeed fault of the fan results in an abort, but an underspeed fault does not. For a resistance change in the dc and ac loads, an offset (i.e., bias) fault

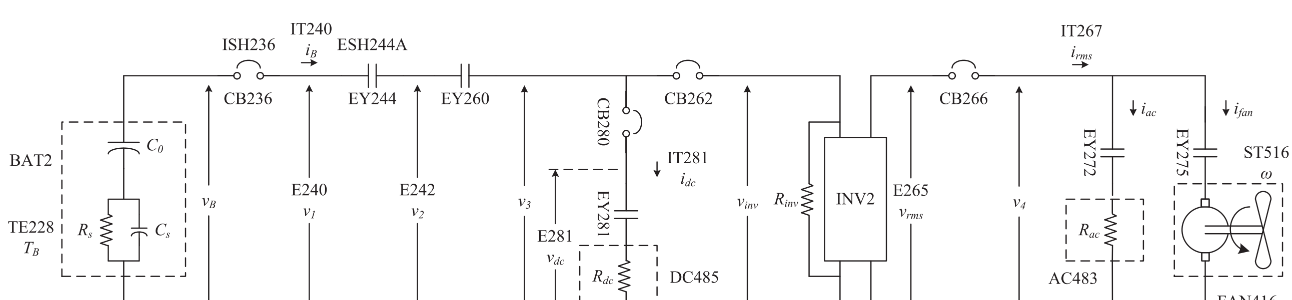

Fig. 1. ADAPT-Lite schematic.