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Diagnosis for uncertain, dynamic and hybrid domains using Bayesian networks and arithmetic circuits

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ABSTRACT

System failures, for example in electrical power systems, can have catastrophic impact on human life and high-cost missions. Due to an electrical fire in Swissair flight 111 on September 2, 1998, all 229 passengers and crew on board sadly lost their lives. A battery failure most likely took place on the Mars Global Surveyor, which unfortunately last communicated with Earth and thus ended its mission on November 2, 2006. Fault diagnosis techniques that seek to hinder similar accidents in the future are being developed in this article. We present comprehensive fault diagnosis methods for dynamic and hybrid domains with uncertainty, and validate them using electrical power system data. Our approach relies on the use of Bayesian networks, which model the electrical power system, compiled to arithmetic circuits. We handle in an integrated way varying fault dynamics (both persistent and intermittent faults), fault progression (both abrupt and drift faults), and fault behavior cardinality (both discrete and continuous behaviors). Our work has resulted in a software system for fault diagnosis, *ProDiagnose*, that has been the top performer in three of the four international diagnostics competitions in which it participated. In this paper we comprehensively present our methods as well as novel and extensive experimental results on data from a NASA electrical power system.

1. Introduction

Historically, electrical power systems (EPSs) have been a major safety concern for people on-board aircraft and spacecraft, and have also caused damage to or loss of unmanned aircraft and spacecraft. Examples of aircraft accidents and incidents include those of Swissair flight 111 and an EasyJet Airbus A319. Because of an electrical fire in Swissair flight 111 on September 2, 1998, all 229 passengers and crew on board tragically lost their lives. On September 15, 2006, an EasyJet Airbus A319 suffered an EPS failure due to a misdiagnosed intermittent fault. Fortunately, the A319 incident did not result in loss of human life or vehicle. An example of an EPS accident on a spacecraft involves the Mars Global Surveyor, where a battery failure most likely took place. The spacecraft last communicated with Earth on November 2, 2006, and NASA officially ended its mission in January 2007.

More generally, a broad range of faults can take place in EPSs of vehicles, and their dynamic and continuous nature often plays a significant role. For example, the dynamics of intermittent and drift faults often make them hard to diagnose. Furthermore, diagnostic systems designed to monitor EPSs often operate in the presence of very little sensed environmental data. To compound these issues, a faulty sensor may give incorrect or extremely noisy readings.

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Fault diagnosis techniques that seek to hinder or reduce the impact of similar future accidents and incidents are being developed in this article. Our work integrates probabilistic computations into diagnosis algorithms [1–5], using Bayesian networks (BNs) [6,7]. BNs provide a solid foundation for a diagnostic system to efficiently compute correct diagnoses when provided incomplete, uncertain, or noisy information or data, for example EPS sensor data. Based on the types of random variables Bayesian networks contain, we can partition BNs into three classes: discrete BNs (with discrete random variables only); continuous BNs (with continuous random variables only); and hybrid BNs (with both discrete and continuous random variables).

Even though it may appear natural to use hybrid BNs in hybrid domains such as EPSs, there are also limitations associated with doing so. The mathematics of hybrid BNs is non-trivial, thus the need to introduce restrictions such as linear Gaussians [8] or resort to approximations [9]. In addition, arithmetic circuits, which we compile our BNs to for purposes of embedded and real-time computing, do not currently support continuous or hybrid BNs.

This article discusses our approach to diagnosis in the presence of incomplete and uncertain information, using BNs [6,7] and arithmetic circuits [10–12] for computation. Our BN models are generated by an algorithm which takes as input a schematic of the physical system to be modeled [13]. These static BN models have been augmented, as discussed in this article, to better support hybrid (in particular, continuous) and dynamic behavior [3,5,14,15]. To meet the challenge of handling hybrid and dynamic behavior using discrete and static BNs, we have developed several novel techniques. Some of these techniques are based on the computation of cumulative sum (CUSUM), a sequential analysis method [16]. We discuss in this article how to use CUSUM as a method for bringing out time-dependent and continuous fault behavior in EPSs, and using CUSUM results as evidence in our static and discrete BNs.

Our diagnostic algorithm *ProDiagnose* takes data from an environment (for example an EPS) and performs real-time diagnostics on the data. We demonstrate our software implementation of ProDiagnose by applying it to data from a real-world EPS called ADAPT [17], located at the NASA Ames Research Center. ADAPT resembles EPSs found in aircraft and spacecraft, and consists of three redundant power sources connected via relays and circuit breakers to two load banks. Also incorporated into ADAPT are different types of sensors that measure various phenomena that reflect the behavior of the EPS's components.

In experiments reported in this article, we show strong diagnostic performance using ProDiagnose, both in terms of accuracy and computational speed. ProDiagnose accuracy results were consistently above 85%, with computation times between 300 and 400 microseconds. Also, the quality of our results did not dramatically drop when ProDiagnose was applied to newer datasets from the ADAPT electrical power system. This shows the potential robustness of our approach to the natural process of electrical power system aging.

ProDiagnose had the best performance in three out of four international diagnostic competitions, arranged at the *20th* and *21st International Workshop on Principles of Diagnosis* (DX-09 and DX-10). The competitions were organized in 2009 and 2010, respectively, and partly focused on ADAPT.[1] In addition to experimental results for the datasets used in these two competitions, we present in this article also results for the 2011 competition, in which ProDiagnose did not compete.

This work is focused on the problem of fault diagnosis in dynamic and hybrid settings, using static and discrete BNs. Unlike some previous work, our use of one health node per component and sensor allows us to avoid the much simplifying single fault assumption.[2] Discrete BNs have previously been used for fault diagnosis in terrestrial EPSs [1,18], although not for the broad range of faults, including abrupt continuous faults, that we stress here. A benefit of using static rather than dynamic BNs is the reduction in model development time as well as computational effort. A benefit of using discrete rather than hybrid Bayesian networks is that we can compile discrete BNs to arithmetic circuits, taking advantage of research advances for arithmetic circuits [10–12].

This article improves and expands upon previous workshop and conference papers [3,5,14,15]. We integrate and tie these previous papers together into a more coherent and comprehensive picture compared to what has been provided earlier. This article presents the ProDiagnose system in its entirety, and provides additional results and details that further explain and validate our models, algorithms, and software. We present results from new experiments, using data from the competition arranged as part of the *22nd International Workshop on Principles of Diagnosis* (DX-11). Our novel experimental results reflect the effect of the aging of ADAPT on ProDiagnose's performance as well as sub-millisecond computation time for diagnosis.

The rest of this article is organized as follows. In Section 2 we briefly review Bayesian networks and arithmetic circuits, related work in diagnosis, and introduce the ADAPT EPS. We discuss in Section 4, using case studies, how and why electrical power systems fail and introduce various fault types found in these systems. Section 5 explains our approach to constructing a Bayesian network model of an electrical power system, and Section 6 presents our diagnosis framework and algorithms, which we call ProDiagnose. Section 7 discusses experimental results, while Section 8 concludes and outlines areas of future research.[3]

[1] See https://sites.google.com/site/dxcompetition2011/ for more information on these competitions, and https://c3.nasa.gov/dashlink/static/media/publication/ijphm-dxc.pdf for a description of the evaluation methods used.

[2] Under the single fault assumption, it is for simplicity assumed that an EPS can only exhibit one fault at a time; multiple concurrent faults are assumed to not happen.

[3] This article is based on previous workshop/conference papers, more specifically [3,5,14,15].