Prognostics Enhanced Reconfigurable Control of Electro-Mechanical Actuators and Related Systems

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ABSTRACT

Modern space and avionics applications require increasingly sophisticated fault-tolerant control systems that are robust, reliable, and relatively inexpensive. Efforts to reduce overall costs and development time of avionics systems in future space explorations have resulted in the widespread use of commercial off-the-shelf (COTS) components (Siewiorek and Narasimhan, 2005). Commercial and military avionics applications are increasingly relying on COTS components as well (Adams, 2005; Jackson *et al.*,). Unfortunately, COTS products introduce a new set of challenges such as reliability, integration and validation, which can offset the cost and complexity COTS solutions are sought to improve. Therefore the need arises for a fault-tolerant control architecture that extends the operating life of COTS components in future avionics systems.

Proposed is a PHM-based framework for adaptive fault-tolerant control. The proposed framework will be designed using a multi-layer open architecture or open control platform (OCP) (Wills *et al.*, 2001). Several OCP designs have been used in the past on unmanned air vehicles (Kannan *et al.*, 1999) and typically consist of three control layers: supervisory, intermediate, and low-level (Wills *et al.*, 2000; Clements *et al.*, 2000; Clements, 2003).

In this application, the supervisory layer will manage high-level objectives, perform system diagnosis (or fault detection and identification) and estimate remaining useful life (RUL) (Isermann, 1997). The intermediate control layer will contain the reconfigurable control which determines the optimal set points to ensure system stability and proper mode-transitioning (Ward *et al.*, 2001; Gokdere *et al.*, 2006). Within this layer an automated contingency management (ACM) module mitigates failures by searching for an optimal control strategy which may vary with time depending on the high-level objectives. The low-level layer will apply set points to the COTS controllers which are assumed to be already available and performing according to their specifications. This layer will execute in real-time to ensure instantaneous mode transitioning.

Communication between all three layers will utilize distributed computing and adaptive resource management techniques allowing for real-time implementation (Doerr *et al.*, 1999). Additionally, verification and validation (V&V) of the system will ensure the controller operates within its design constraints, fault-modes are diagnosed correctly, and mode transitions occur properly .

Implementation of the proposed control architecture requires enabling technologies for data acquisition, feature extraction, fault detection and isolation, failure prognosis, adaptive control, and V&V. Preprocessing techniques, such as denoising, will be explored to condition sensor data. Features will be extracted from the acquired data by performing time analysis, frequency/spectral analysis, and wavelet analysis (Zhang *et al.*, 2008). Bayesian reasoning, fuzzy logic, particle filtering and neural network techniques will be explored to detect and identify fault modes. Failure prognosis will be performed by combining particle filtering with the component fault models to generate probability density functions (pdf) of remaining useful life (RUL) (Orchard, 2007; Orchard *et al.*, 2008).

The final control will be able to predict RUL for the system to within a specific confidence interval and false alarm rate specified by the end-user (or application requirements). Anticipated failures will be mitigated by applying a time-varying multi-objective criterion function and appropriate constraints to determine the optimal reconfiguration of low level controllers (Bogdanov *et al.*, 2006; Zhou *et al.*, 1996). This will allow for extended system usability, or RUL, while maintaining high-priority objectives at the expense of relaxing low-priority objectives. Model verification and validation shall evaluate the reconfiguration strategy to ensure the major, or high priority, control objectives are achieved.

Benefits The proposed PHM based fault-tolerant adaptive control framework will be usable across many avionics application domains directly applicable to aero propulsion, power systems, unmanned air vehicles and future generation avi-

ation platforms. Additionally, ability to predict RUL in specific components and subsystems and accommodate for impending failures will minimize the occurrence of unexpected, costly and possible life-threatening mission failures; reduce the number of unnecessary maintenance actions; and extend the usability of the system (Zhang and Jiang, 2008).

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