Workshop Proposal for ACC-2007
Marriott Marquis Hotel at Times Square
New York City, USA
July 11-13, 2007

Title: Diagnostics, Prognostics, and Health Management (DPHM): from theory to practice

Organizer:

Intelligent Automation, Inc.
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This workshop will focus on current state of the art in **Diagnostics, Prognostics, and Health Management (DPHM)** and the application of these ideas to a wide variety of problems. The proposed workshop will last for day and will be represented by speakers from industry (IAI), academia (Penn State and Georgia Tech) and government (ARL and NASA).

Length of the workshop: One Day
Intended Audience: Anyone and everyone interested in the topic of Diagnostics Prognostics and Health management (DPHM). Specifically people working in the area of health monitoring and Maintenance.
Background : Basic Engineering and Mathematics background
What they walk away with:

- Current and future trends in the area of Diagnostics, Prognostics, and Health Management (DPHM)
- Solutions to a wide class of health management problems with industrial applications, specifically the health management of the following will be covered
    - Gas turbine engines
    - Wiring systems in aging aircrafts
    - Electrical Systems
- Pervasive Fault Tolerance in Networked System-of systems
- Knowledge of a newly emerging field of Symbolic Time Series Analysis for anomaly detection.

Tentative Schedule

9.00 A.M. -9.30 A.M. Opening remarks-Introduction: Dr. Eric van Doorn, Intelligent Automation Inc (IAI)

9.30 A.M.-10.30A.M. An Integrated Architecture for Fault Diagnosis and Failure Prognosis of Engineering Systems, Dr. George Vachtsevanos, Georgia Tech.

10.30 A.M. -10.45 A.M. Coffee break

10.45A.M. -12.00 P.M. Anomaly Detection and Failure Mitigation in Human-Engineered Complex Systems (part -1)
Dr. Asok Ray, Pennsylvania State University

12.00 P.M. -1.00 P.M. Lunch Break

1.00 P.M.-2.00 P.M. Anomaly Detection and Failure Mitigation in Human-Engineered Complex Systems (part -2)
Dr. Asok Ray, Pennsylvania State University

2.00 P.M.-2.15 P.M. Coffee break

2.15 P.M.- 3.15 P.M. Pervasive Fault Tolerance in Networked System-of systems
Dr. Shashi Phoha, ARL

3.15 P.M.- 4.15 P.M. Prognosis and Life Extension of Aircraft Gas Turbine Engines
Jonathan Litt

4.15 P.M.-4.30 P.M. Coffee break

4.30 P.M.-5.30 P.M. Integrated Diagnostics, Prognostics, and Health Management (DPHM) for aircraft wiring
Dr. Devendra Tolani, Intelligent Automation Inc (IAI)

Summary of Presentations

(1) An Integrated Architecture for Fault Diagnosis and Failure Prognosis of Engineering Systems

Dr. George Vachtsevanos

This presentation is introducing a novel integrated methodology for data processing, feature or Condition Indicator (CI) selection and extraction, fault diagnosis and failure prognosis for critical engineering systems. It is intended to provide a holistic approach to the on-line health monitoring and condition assessment of such critical assets as aircraft, ground vehicles, gas turbines, etc. We will introduce those essential modules of the architecture that are employed sequentially to synthesize the overall Condition Based Maintenance or Prognostics and Health Management system. The output of the system may be used by the operator (pilot, for example) to take immediate action to avoid a catastrophic event or the maintainer in order to schedule optimally maintenance. The results of the proposed scheme may also assist the system designer in the pursuit of more fault-tolerant and high-confidence systems. Generic aspects of the methodology are applicable to a wide range of engineering systems.

The enabling technologies involve the selection and extraction of condition indicators from raw vibration data in the time, frequency and wavelet domains. Intelligent techniques are employed to prioritize and select the optimum feature vector. A Bayesian estimation approach, called particle filtering, is introduced to detect incipient failures and predict the time to failure of failing components. The diagnosis and prognosis modules build upon physics based models of the system and actual measurements for early fault detection and accurate/precise failure prediction. The integrated architecture – data processing, diagnosis and prognosis – runs in real time providing the operator and maintainer useful information. The methodology has been successfully tested and validated in a "blind" test environment with actual data obtained from a seeded fault experiment. Results from such testing will be presented that illustrate the validity and effectiveness of the tools. The architecture is currently at a TRL level 6. We will employ examples from a helicopter main transmission and an automobile electrical storage and distribution system to demonstrate the effectiveness of the approach.

(2) Anomaly Detection and Failure Mitigation in Human-Engineered Complex Systems

Dr. Asok Ray

Engineering theories of control, communication and computation have matured in recent decades facilitating creation of systems of bewildering complexity, which are almost comparable to biological systems. The complexity is often hidden and cryptic in the laboratory environment as well as during nominal operations of large-scale dynamical systems; however, it may become acutely conspicuous when contributing to rare cascading faults. From these perspectives, anomaly is defined as deviation from the nominal behavior and is associated with parametric or non-parametric changes that may gradually evolve. Early detection of anomalies in complex dynamical systems, such as future-generation *Aerial Vehicles*, is essential not only for prevention of catastrophic failures and mission disruption, but also for robust performance, life extension, and self healing.

The seminar will narrate some of the research experience on Anomaly Detection and Failure Mitigation in Human-engineered Complex Systems under a current Multidisciplinary University

Research Initiative (MURI) grant from Army Research Office (ARO). The first part of the seminar will focus on theoretical formulation and experimental validation of Symbolic Time Series Analysis (STSA) for early detection of potentially malignant anomalies in real time. The second part of the seminar will use this information for failure mitigation and accommodation via discrete-event supervisory control.

The concept of STSA-based anomaly detection is built upon the theories of Symbolic Dynamics, Statistical Mechanics, and Information Theory. The key idea is identification of behavior patterns from symbolic sequences, derived from time series data, through finite-state machines having the structure of the *generalized Ising (Potts)* model; this is accomplished by taking advantage of non-linear and non-stationary features of the dynamical system. The underlying principle of anomaly detection is analogous to the canonical ensemble theory of microstates under thermodynamic equilibrium for quasi-stationary behavior as well under phase transitions. The anomaly detection concept will be first illustrated using an example of a second-order forced Duffing equation where the dissipation parameter is slowly varying and small parametric changes are captured much before the onset of chaotic motion (i.e., period doubling) at a bifurcation point. Then, the efficacy of anomaly detection will be demonstrated on experimental data sets of fatigue crack damage in polycrystalline alloys.

The concept and formulation of a signed real measure of regular languages will then be presented for synthesis of discrete-event robust optimal supervisors that use the anomaly information. The measure is constructed based upon the principles of automata theory and real analysis for quantitative evaluation and comparison of the controlled behavior of discrete-event dynamical systems. The language measure creates a total ordering on the performance that provides a precise quantitative comparison of the plant behavior under different supervisors. Total variation of the language measure serves a metric for the vector space of sublanguages of the regular language.

(3) Pervasive Fault Tolerance in Networked System-of systems
Dr. Shashi Phoha

The physics of individual failure in a component cannot sufficiently explain the pathological behaviors observed in complex human-engineered system-of-systems. Complex macroscopic behaviors emerge as a consequence of the nonlinear dynamics of interactions among linked components. System behaviors may range from strict order to chaos with great sensitivity to initial conditions embedded in the physics of individual faults. This workshop segment will address fundamental principles of pervasive fault tolerance in such human engineered complex dynamic systems, and formulate architectures, tools, and algorithms for achieving and validating operational dependability in such systems through design and adaptive operation. Research results of applications to sensor networks and experiments on fixed and mobile robotic platforms for DARPA, NSF, ONR and ARO projects will be presented to ascertain the state of the art. Research challenges and many potential applications that will drive research in this area will also be discussed.

(4) Prognosis and Life Extension of Aircraft Gas Turbine Engines
Mr. Jonathan Litt

Integrated Resilient Aircraft Control (IRAC) is an initiative under NASA's new Aviation Safety Program. The main objective of the propulsion system portion of this research area focuses on how engine control systems can improve aircraft safe-landing under adverse conditions.

Gas turbine engines are designed to provide sufficient safety margins to guarantee robust operation with an exceptionally long life. This is achieved in part by the use of a Full Authority Digital Engine Controller (FADEC) which combines state-of-the-art computer technologies with sensor and actuator technologies to ensure reliable, robust engine operation over a wide range of operating conditions. The FADEC and its control laws are designed to optimize the fuel efficiency while maintaining conservative operating margins to guarantee good fuel consumption and adequate engine life usage.

However, engine performance requirements may be drastically altered during abnormal flight conditions or emergency maneuvers. In some situations, engines may be required to generate higher than certified levels of thrust. In other situations, pilots may require more responsive engine thrust than can be achieved within the limits of the original controller design. Pilots may also require the continued operation of a slightly damaged engine to bring the aircraft back safely. Thus during abnormal flight situations, the conservative design of the engine and its control system may no longer be in the best interest of overall aircraft safety. In situations like these, it must be possible to sacrifice engine life in order to increase the chances of survival of the vehicle and its passengers.

Adaptive engine control methodologies to operate the engine beyond the normal domain, and to operate engines with discrete damage under abnormal flight conditions, will be described. The long term objective of the propulsion research under IRAC is to develop an enhanced engine capability with an adaptive controller to enable a fully integrated flight and propulsion control system for safe operation and landing of aircraft under abnormal conditions.

Some of the areas that will be described include the study of possible failure modes associated with the enhanced engine operation, life modeling of the critical components, and operability margin management. Additionally, control strategies for enhanced engine operation which include thrust boost, faster response, and damaged engine operation will be discussed. The designed controller shall include different operating modes for different emergency conditions. This also enables the engine controller play an active role under the flight control. This can include the direct command from the flight controller for thrust differential to utilize the engine pair as a redundant set of flight actuators. The thrust management will also include the life/performance trade-off evaluation and optimization for the constraints specified by the flight controller.

(5) Integrated Diagnostics, Prognostics, and Health Management (DPHM) for aircraft wiring
Dr. Devendra Tolani, Ph.D.

Current generation technology is making advances in the diagnosis and prognosis of aircraft wiring faults, but has started to exhaust the capabilities of time domain reflectometery, frequency domain reflectometery, and standing wave ratio technologies. These technologies have demonstrated the ability to detect opens and shorts, and their abilities to locate these faults are improving. Unfortunately, they have not been able to successfully demonstrate the ability to reliably detect latent faults, detect faults in branched circuits, and locate these faults on active circuits. In this talk, we report on a novel and radical extension of Time Domain Reflectometry as applied to the detection and location of flaws in (aircraft) wiring systems. Our approach marries the two methods most commonly used for the inspection of conducting structures: TDR, and Eddy Current Testing (ECT). In many ways, TDR and ECT appear to be orthogonal methods. By combining them, key advantages of both (testing at distance for TDR, and sensitivity for ECT) are retained while avoiding some of their limitations. In addition we are extending our TDR development to testing of optical fibers, and the health monitoring of wires in high-temperature environments. We propose an innovative scheme involving layering of ceramics, ceramic matrix composites, metal matrix composites and fiber optics assembly with ceramic fiber sheaths. This work is supported by Navair, Air Force Research Laboratory and DOT**.**

Speakers

Dr. George Vachtsevanos	**Dr. Asok Ray**	**Dr. Shashi Phoha**	**Mr. Jonathan Litt**	**Dr. Devendra Tolani**
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