• SUMMARY For NF1676A Number 173

• VENUE: 01 Conference Paper - Infotech@Aerospace

• TITLE: General Purpose Data-Driven Monitoring for Space Operations

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• ABSTRACT: As modern space propulsion and exploration systems improve in capability and efficiency, their designs are becoming increasingly sophisticated and complex. Determining the health state of these systems, using traditional parameter limit checking, model-based, or rule-based methods, is becoming more difficult as the number of sensors and component interactions grow. Data-driven monitoring techniques have been developed to address these issues by analyzing system operations data to automatically characterize normal system behavior. System health can be monitored by comparing real-time operating data with these nominal characterizations, providing detection of anomalous data signatures indicative of system faults or failures.

Data-driven techniques have a number of advantages over other methods for monitoring complex space vehicles. Unlike model-based systems, the developer does not need to understand or encode the internal operation of the system. The knowledge required to monitor the system is automatically derived from archived data from system operation. Unlike rule-based systems, data-driven systems do not require system analysts to define nominal relationships among sensors. Analysts can and often do determine these relationships for a system with few sensors; it is more difficult to analytically determine the nominal relationship among a large number of sensors. Data-driven techniques are not limited to low-dimensional spaces and work as effectively with dozens of parameters as they do with a few. Knowledge bases formed by data-driven techniques are also easy to update. As the operating envelope of the monitored system is expanded, data-driven techniques can be quickly retrained to incorporate the new behavior into the knowledge base. The expertise and time-consuming process of updating a model or rule base to maintain consistency with the new operation is not required.

The Inductive Monitoring System (IMS) is a data-driven system health monitoring software tool that has been successfully applied to several aerospace applications. IMS uses a data mining technique called clustering to analyze archived system data and characterize normal interactions between parameters. This characterization, or model, of nominal operation is stored in a knowledge base that can be used for real-time system monitoring or analysis of archived events. System data is compared with the nominal IMS model to produce a measure of how well current system behavior matches the normal behavior defined by the training data. Significant deviations from the nominal system model can provide alerts to system malfunctions or precursors of significant failures.
The scope of IMS based data-driven monitoring applications continues to expand with current development activities. Successful IMS deployment in the International Space Station (ISS) flight control room to monitor ISS attitude control systems has led to applications in other ISS flight control disciplines, such as thermal control. It has also generated interest in data-driven monitoring capability for Constellation, NASA's program to replace the Space Shuttle with new launch vehicles and spacecraft capable of returning astronauts to the moon, and then on to Mars. Several projects are currently underway to evaluate and mature the IMS technology and complementary tools for use in the Constellation program. These include an experiment on board the Air Force TacSat-3 satellite, and ground systems monitoring for NASA's Ares I-X and Ares I launch vehicles.

The TacSat-3 Vehicle System Management (TVSM) project is a software experiment to integrate fault and anomaly detection algorithms and diagnosis tools with executive and adaptive planning functions contained in the flight software on-board the Air Force Research Laboratory TacSat-3 satellite. The TVSM software package will be uploaded after launch to monitor spacecraft subsystems such as power and guidance, navigation, and control (GN&C). It will analyze data in real-time to demonstrate detection of faults and unusual conditions, diagnose problems, and react to threats to spacecraft health and mission goals. The experiment will demonstrate the feasibility and effectiveness of integrated system health management (ISHM) technologies with both ground and on-board experiments. Initially, the TVSM software will run open loop, providing system health information and recommendations to ground operators, without automatically performing fault-mitigating corrective actions. After the end of the satellite's mission, closed loop tests combining TVSM monitoring and diagnosis with reactive capabilities by the flight software will be performed. In addition to monitoring for long periods of actual operation, the experiment will include fault injection into TacSat-3 data as well as commanded operations to test and evaluate automatic ISHM monitoring and recovery under controlled conditions.

The ongoing Ares I-X Ground Diagnostics Prototype project is evaluating the same set of software tools as the TVSM project. They will be used for detecting and diagnosing faults in the Ares I-X first-stage solid rocket booster (SRB) thrust-vector control (TVC) system and associated ground support equipment. These tools will be used at the Kennedy Space Center (KSC) during Ares I-X vehicle integration and testing activity in the vehicle assembly building (VAB) and while the vehicle is on the launch pad. IMS will be integrated with two other software tools: TEAMS, a model-based reasoning tool from Qualtech Systems Inc., and SHINE (Spacecraft Health Inference Engine), a rule-based expert system from the Jet Propulsion Laboratory (JPL). SHINE rules will be used to determine TVC system operating modes. IMS will have a