SOFTWARE TOOLS TO SUPPORT THE ASSESSMENT OF SYSTEM HEALTH

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This presentation provides an overview of three software tools that were developed by the NASA Glenn Research Center to support the assessment of system health: the Propulsion Diagnostic Method Evaluation Strategy (ProDIMES), the Systematic Sensor Selection Strategy (S4), and the Extended Testability Analysis (ETA) tool. Originally developed to support specific NASA projects in aeronautics and space, these software tools are currently available to U.S. citizens through the NASA Glenn Software Catalog.

The ProDiMES software tool was developed to support a uniform comparison of propulsion gas path diagnostic methods. Methods published in the open literature are typically applied to dissimilar platforms with different levels of complexity. They often address different diagnostic problems and use inconsistent metrics for evaluating performance. As a result, it is difficult to perform a one-to-one comparison of the various diagnostic methods. ProDIMES solves this problem by serving as a theme problem to aid in propulsion gas path diagnostic technology development and evaluation. The overall goal is to provide a tool that will serve as an industry standard, and will truly facilitate the development and evaluation of significant Engine Health Management (EHM) capabilities. ProDiMES has been developed under a collaborative project of The Technical Cooperation Program (TTCP) based on feedback provided by individuals within the aircraft engine health management community.

The S4 software tool provides a framework that supports the optimal selection of sensors for health management assessments. S4 is structured to accommodate user-defined applications, diagnostic systems, search techniques, and system requirements/constraints. One or more sensor suites that maximize this performance while meeting other user-defined system requirements that are presumed to exist. S4 provides a systematic approach for evaluating combinations of sensors to determine the set or sets of sensors that optimally meet the performance goals and the constraints. It identifies optimal sensor suite solutions by utilizing a merit (i.e., cost) function with one of several available optimization approaches. As part of its analysis, S4 can expose fault conditions that are difficult to diagnose due to an incomplete diagnostic philosophy and/or a lack of sensors. S4 was originally developed and applied to liquid rocket engines. It was subsequently used to study the optimized selection of sensors for a simulation-based aircraft engine diagnostic system.
The ETA Tool is a software-based analysis tool that augments the testability analysis and reporting capabilities of a commercial-off-the-shelf (COTS) package. An initial diagnostic assessment is performed by the COTS software using a user-developed, qualitative, directed-graph model of the system being analyzed. The ETA Tool accesses system design information captured within the model and the associated testability analysis output to create a series of six reports for various system engineering needs. These reports are highlighted in the presentation. The ETA Tool was developed by NASA to support the verification of fault management requirements early in the Launch Vehicle process. Due to their early development during the design process, the TEAMS-based diagnostic model and the ETA Tool were able to positively influence the system design by highlighting gaps in failure detection, fault isolation, and failure recovery.
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Outline

- Background
- Software Tools
  - Propulsion Diagnostic Method Evaluation Strategy (ProDIMES)
  - Systematic Sensor Selection Strategy (S4)
  - Extended Testability Analysis (ETA) Tool
- Concluding Remarks
- References
Active Clearance Control
- Clearance Modeling
- Mechanical/Smart Materials
- Actuation Requirements

Active Flow Control
- High Bandwidth Actuation
- Stall Control
- Smart Vanes
- Turbine Film Cooling Control

Active Combustion Control
- Emission Minimization
- Control of Thermo-acoustic Instability

Advanced Control Logic
- Intelligent Adaptive Control
- Life Extending Control
- Resilient Propulsion Control

System Health Management for Propulsion, Power, & Ground Systems
- Sensor Selection & Validation
- Fault Diagnosis & Classification
- Prognostics
- Post Test Diagnostic Systems
- Communication Requirements
- Real-Time Implementation Issues

Maintainability & Reliability
- Autonomous Mobile Robotic Inspection & Repair

Dynamic Modeling

Current NASA Programs

Aeronautics Research Mission
- Fundamental Aeronautics
- Aviation Safety

Exploration Systems Mission
- Space Launch System
- Ground Systems Development and Operations

Advanced Propulsion Concepts
- Pulse Detonation Engine
- Fuel Cell Powered Aircraft
- Wave Rotors
- High-speed Systems
**ProDIMES:** Propulsion Diagnostic Method Evaluation Strategy
Supports fair, quantitative benchmark comparisons of aero engine gas path diagnostic methods.

**S4:** Systematic Sensor Selection Strategy
Software framework for performing optimal selection of sensors required to support system health assessment

**ETA Tool:** Extended Testability Analysis Tool
Testability analyses that support qualitative verification of system health requirements early in the design process.
Acknowledgements

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**S4: Systematic Sensor Selection Strategy**

**ETA Tool:** Extended Testability Analysis Tool

**ProDIMES:** Propulsion Diagnostic Method Evaluation Strategy
Engine Health Management (EHM) related R&D activities have increased significantly since the late 1990’s. However, due to the use of different terminologies, applications, proprietary data, and metrics there is no basis of comparison.

Public benchmarking problems can facilitate the development and comparison of candidate health management methods against a common problem.

ProDiMES provides a simulated aircraft engine gas path diagnostic benchmarking problem:
- Developed as part of a collaborative project under The Technical Cooperation Program (TTCP)
- Available through the NASA Glenn Software Catalog

ProDiMES Architecture
Propulsion Diagnostic Method Evaluation Strategy (ProDiMES)

ProDiMES Diagnostic Benchmarking Process

ProDiMES enables independent development and evaluation and a blind test case comparison

ProDiMES Public Benchmarking Process

1a. Engine fleet simulator: Enables user to specify the type and number of gas path fault cases.

1b. Blind test cases: User has no a priori knowledge of fault existence or fault type

2. Solution providers apply their individual diagnostic solutions

3. Evaluation Metrics: Defined and applied to provide a uniform assessment of performance

4. Results: archived in common format

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**Propulsion Diagnostic Method Evaluation Strategy (ProDiMES)**

**Commercial Modular Aero-Propulsion System Simulation**

- Engine model representative of a large commercial turbofan
- NASA-developed, Matlab/Simulink-based, generic, non-linear, component-level model with closed-loop control
- Uses 13 health parameters to model engine performance degradation due to engine wear and faults.
- Generates 11 sensed outputs
  - 3 aircraft parameters (Pamb, P2, T2)
  - 8 engine measurements (Nf, Nc, P24, Ps30, T24, T30, T48, Wf36)
- ProDIMES EFS uses core elements of C-MAPSS:
  - Steady-state solver balances engine to specified operating point
  - No closed-loop control logic or transient operating capability
  - Includes logic to ensure that operating limits are not violated
  - Captures coupled fault effects (e.g., a corrected rotor speed sensor fault will result in mis-scheduled variable geometry).
A 2012 workshop was held for ProDiMES users to share diagnostic results and lessons learned.
- ProDiMES was found to provide a suitably challenging problem.
- Users welcomed the opportunity to assess and compare diagnostic methods against a standard benchmark problem.

The results of four diagnostic methods applied to the blind test case data set were assessed and compared (a portion of the metric results are shown below).
- Follow-on collaborative assessments conducted by ProDiMES participants have shown improved diagnostic performance obtained by pairing the best performing detection and classification approaches.

**Propulsion Diagnostic Method Evaluation Strategy (ProDiMES)**

**ProDiMES Blind Test Case Comparison Results**
NASA Glenn Controls & Dynamics Branch
Software Tools for System Health Assessment

**ProDIMES:** Propulsion Diagnostic Method Evaluation Strategy

**S4:** Systematic Sensor Selection Strategy

**ETA Tool:** Extended Testability Analysis Tool

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Motivation for Optimizing Sensor Selection

• Traditional aerospace approaches to sensor selection are:
  – Generally qualitative approaches based on engineering judgment and/or heuristics
  – Oriented toward operations, controls and/or performance
  – May not provide coverage required to manage system health

• Systematic Sensor Selection Strategy (S4)
  – Used in simulation-based studies to optimally identify sensors needed to manage the health of liquid rocket engines (MC-1, RS-83, RS-84, X-34) and aircraft turbine engines.
  – Model-based approach identifies a set of sensors that optimally meets application-specific design objectives
  – Single-valued user-defined metric (i.e., cost) function employed to quantitatively assess capability of various sensor combinations to meet multiple design objectives
  – Flexible two-stage optimization approach with broad applicability
S4 Framework

Iterative Down-Select Process

Candidate Sensor Suites

System Diagnostic Model ➔ Sensor SuiteMerit Algorithm ➔ Down-Select Algorithm

Candidate Selection Complete

No ➔ Yes

Final Selection Process

Collection of Effective Sensor Suites

Statistical Evaluation Algorithm

Optimal Sensor Suite

Knowledge Base

Performance Related Information ➔ System Simulation

Application Specific  Non-Application Specific
Generalized S4 Implementation Process

- Eight-step process defined as *guideline* for implementing elements of the S4 framework as part of a user-defined application
- Significant flexibility – early steps can be reordered at user’s discretion
- Some iteration likely during implementation of early steps
- Detailed description of implementation process contained in NASA/CR—2012-215242 S4 User Guide (see references)
S4 Use Case Implementation (1/3)

Step 1: Knowledge Acquisition

– Goal: Collect data required to implement user’s S4 application
– S4 C-MAPSS Use Case
  • Optimization based on seven (7) control sensors and five (5) candidate sensors
  • Data for four (4) fault cases: fan, high pressure compressor, high pressure turbine, and low pressure turbine.
  • Each fault modeled as simultaneous adjustments to associated C-MAPSS efficiency and flow capacity health parameters.
  • Model reference & test case data
    – Used to assess sensor suite failure detection and fault isolation.
    – Data conditioning improves algorithm stability
S4 Use Case Implementation (2/3)

Step 2: Define Sensor Suite Merit Algorithm

– Goal: Define algorithm that will be used to quantify optimality
– S4 C-MAPSS Use Case

For each sensor suite $k$

$$M_k = P_k \cdot D_k = \frac{1}{w_k \cdot |N_d - N_k| + 1} \cdot \sum_{j=1}^{n} C_j Z_{jk}$$

where

- $M_k$ Merit Value – Value of the Merit Algorithm for sensor suite $k$.
- $P_k$ Penalty Term – Reduces merit value ($M_k$) as number of sensors in suite $k$ deviates from the preferred number of sensors, $N_d = 9$.
- $D_k$ Diagnostic Performance Score – Provides quantitative assessment of the diagnostic performance of sensor suite $k$.
- $C_j$ Criticality Factor – Weighting term for fault case $j$ based on fault criticality and/or probability of occurrence. For this use case = 1.
- $Z_{jk}$ Fault Diagnostic Performance Metric – Qualitative assessment of the diagnostic performance of sensor suite $k$ for fault case $j$. 
S4 Use Case Implementation (3/3)

Steps 7 & 8: Create/Perform Iterative Down-Select & Final Selection Processes

– Goal: Develop and execute software code for processes that perform the optimization.
– S4 C-MAPSS Use Case
  • Iterative Down-Select Process
    – Implemented with Genetic Algorithm
    – After 5 generations, highest performing sensor suites are identified
  • Final Selection Process
    – Selected 3 highest performing sensor suites for more rigorous evaluation
    – Confirms results of Iterative Down-Select Process

<table>
<thead>
<tr>
<th>Sensor Suite Merit Value</th>
<th>Add’l Candidate Sensors</th>
<th>Iterative Down-Select Process</th>
<th>Final Selection Process</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T50, P50</td>
<td>23.0418</td>
<td>22.4238</td>
</tr>
<tr>
<td></td>
<td>P25, T50</td>
<td>22.0360</td>
<td>20.8636</td>
</tr>
<tr>
<td></td>
<td>P25, P50</td>
<td>22.0360</td>
<td>20.8636</td>
</tr>
</tbody>
</table>
NASA Glenn Controls & Dynamics Branch

Software Tools for System Health Assessment

**ProDIMES**: Propulsion Diagnostic Method Evaluation Strategy

**S4**: Systematic Sensor Selection Strategy

**ETA Tool**: Extended Testability Analysis Tool
Model-based Testability Analysis

Motivation

– Multiple system-level goals for Safety, Reliability, Maintainability and Availability lead to various diagnostic-related requirements levied against the system or subsystem.

Benefits

– Model-based verification of diagnostic requirements early in the design process enables redesign when cost impacts are lower.

Approach

– TEAMS Designer (commercial-off-the-shelf software) used to model fault propagation via directed graph theory.

Model-based Testability Analysis

– Qualitative diagnostic approach based on a fault propagation model of the system
– Generates Dependency Matrix that relates failure modes to failure detection tests

DIRECTED GRAPH

Faults propagate in forward direction and are detected by “tests”

Isolation/Classification results from moving backward thru the graph.
ETA Tool Overview

Qualitative Functional Fault Model with Testability Analysis

Extended Testability Analysis (ETA) Tool

<table>
<thead>
<tr>
<th>Gov't Dev. Effort</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stand-alone software tool developed to support Ares Program</td>
</tr>
<tr>
<td>Provides additional analyses and detailed reporting capabilities</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Commercialization Effort</th>
</tr>
</thead>
<tbody>
<tr>
<td>Government/Industry partnership integrated ETA tool modeling conventions, analyses, and reports into existing COTS software package to support future NASA programs.</td>
</tr>
</tbody>
</table>

Failure Detectability
Test Utilization
Failure Isolation
Component Failure Isolation
Effect Mapping
Sensor Sensitivity

Stand-alone software available from the NASA Glenn Software Catalog at: https://sr.grc.nasa.gov

Failure Mode Tests

<table>
<thead>
<tr>
<th>Modes</th>
<th>1</th>
<th>0</th>
<th>1</th>
<th>1</th>
<th>0</th>
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<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Schematic + FMEA
COTS Modeling Software
Dependency Matrix (D-Matrix)
ETA Tool Use Case
Fault Isolation Report Detail

- Failure modes are grouped by their “detection signature” – the set of tests that detect the propagated effects
- Fault isolation information can be used to verify Caution & Warning or Launch Commit Criteria (LCC) strategies when detection must identify a specific set of failure modes.

<table>
<thead>
<tr>
<th>Failure Mode Group #22</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection Signature: 3 Tests</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sensor Identifier</th>
<th>Schematic Identifier</th>
<th>Sensor Description</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEN0026</td>
<td>D4</td>
<td>Yaw LVDT Displacement Transducer 1</td>
<td>No Position Change</td>
</tr>
<tr>
<td>SEN0027</td>
<td>D5</td>
<td>Yaw LVDT Displacement Transducer 2</td>
<td>No Position Change</td>
</tr>
<tr>
<td>SEN0028</td>
<td>D6</td>
<td>Yaw LVDT Displacement Transducer 3</td>
<td>No Position Change</td>
</tr>
</tbody>
</table>

Failure Mode Group contains 2 Failure Mode(s)

<table>
<thead>
<tr>
<th>System</th>
<th>Component</th>
<th>Failure Mode</th>
<th>FMEA Identifier</th>
<th>Criticality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vector Control System</td>
<td>Power Valve</td>
<td>Stuck In NULL Position</td>
<td>MS-SS-ACT-02-002</td>
<td>1</td>
</tr>
<tr>
<td>Vector Control System</td>
<td>Yaw Actuator</td>
<td>Actuator Locked In Place</td>
<td>MS-SS-ACT-03-001</td>
<td>1</td>
</tr>
</tbody>
</table>
# ETA Tool Use Case

## Fault Isolation Report Summary

### Ambiguity Analysis

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Failure Mode Groups</td>
<td>61</td>
</tr>
<tr>
<td>Number of Failure Modes</td>
<td>118</td>
</tr>
<tr>
<td>Number of Isolated Groups</td>
<td>50</td>
</tr>
<tr>
<td>Maximum Failure Mode Group Size</td>
<td>15</td>
</tr>
<tr>
<td>Calculated Ambiguity Score</td>
<td>55</td>
</tr>
</tbody>
</table>

### Ambiguity Distribution (Failure Mode Level)

<table>
<thead>
<tr>
<th>Group Size</th>
<th>Percentage of Groups</th>
<th>Number of Groups</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>81.97%</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>6.56%</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3.28%</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>3.28%</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1.64%</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>3.28%</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

Note: This breakdown is by Failure Mode. Undetected Failure Modes are not included in this exercise.
Concluding Remarks

- NASA Glenn developed software tools available to U.S. Citizens through the NASA Glenn Software Catalog/Repository (http://sr.grc.nasa.gov).
- Software Catalog includes software tools developed by the Controls and Dynamics Branch to support the assessment of System Health.
  - **ProDIMES** provides approach for fair, quantitative benchmark comparisons of aero engine gas path diagnostic methods.
  - **S4** provides software framework for optimally selecting sensors required to support the assessment of system health.
  - **ETA Tool** augments commercial-off-the-shelf software to provide testability analyses that support qualitative verification of system health requirements early in the design process.
- For more information contact kjmelcher@nasa.gov
References for ProDIMES


References for S4


References for ETA Tool

