Integrated Architecture for Aircraft Engine Performance Monitoring and Fault Diagnostics: Engine Test Results

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Overview

• Background
• Architecture
• Application
• Results
• Conclusion
Background – aircraft engine performance trend monitoring and gas path fault diagnostics

• Conventional Approach:
  – Ground-based
  – Processing of “snapshot” measurements post-flight
  – Enables estimation and trending of engine performance and gas path fault diagnostics
  – Early diagnosis of incipient fault conditions with minimal latency can be challenging

• Emerging Approach:
  – Advances in on-board processing and flight data recording capabilities are enabling new diagnostic approaches
  – Acquisition of full-flight streaming/continuous measurement data now possible
  – Requires new approaches to analyze expanded quantity and format of data

Example Aircraft Engine Flight Data

- Denotes notional “snapshot” measurement point
Architecture for Engine Performance Monitoring and Fault Diagnostics

- Designed for processing real-time continuous (streaming) engine measurement data to provide:
  - Estimation and trending of deterioration-induced engine performance changes
  - Detection and isolation of gas path system faults
Real-Time Self Tuning Model

- Self-tuning piecewise linear Kalman filter design
- Applies NASA-developed optimal tuner selection
  - Application for underdetermined estimation problems
  - Minimizes mean squared estimation error in parameters of interest
- Provides real-time estimates of unmeasured engine performance parameters
Performance Baseline Model

- Piecewise linear state space model design, open-loop with inputs:
  - Actuator commands, \( u \).
  - Power reference parameter, \( y_r \), which is used to improve model-to-engine tracking capability.
  - Periodic model tuning parameter updates from RTSTM to account for gradual degradation effects.
- PBM provides a baseline of recent engine performance
Fault Diagnostics

- Monitors residuals between sensed engine outputs and PBM estimated outputs.
- Fault detection is performed by calculating and monitoring a weighted sum of squared residuals (WSSR) signal. \( WSSR = \hat{\mathbf{y}}^T \mathbf{R}^{-1} \hat{\mathbf{y}} \)
- Upon fault detection, fault classification is performed by identifying the candidate fault signature that most closely matched the observed residual in a weighted least squares sense. \( WSSEE_j = (\tilde{\mathbf{y}} - \hat{\mathbf{y}})_j \mathbf{R}^{-1} \left( \tilde{\mathbf{y}} - \hat{\mathbf{y}}_j \right) \)
Fault Diagnostics

At each time sample a new WSSR and WSSEE are calculated.
Fault Diagnostics

The smallest $WSSEE$ value is classified as the fault type.
Application Example: Analysis of Vehicle Integrated Propulsion Research (VIPR) Engine Test Data

• VIPR is a series of ground-based, on-wing engine tests to mature engine health management sensors and algorithms
  – Ongoing at NASA Armstrong / Edwards Air Force Base
  – Partners include NASA, US Air Force, Pratt & Whitney, and others

• Test vehicle:
  – Boeing C-17 Globemaster III
  – Equipped with Pratt & Whitney F117 high-bypass turbofan engines

• VIPR ground tests include:
  – A series of nominal and seeded faulted engine test cases
    o Faults include station 2.5 bleed valve and 14th stage bleed valve faults
  – Data collected over a range of engine power settings including steady-state and transient operating conditions
Model-Based Gas Path Diagnostic Architecture

- Architecture Designed Based on NASA C-MAPSS40k Engine Model

### Gas Path Sensor Measurements

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
<td>fan speed</td>
</tr>
<tr>
<td>N2</td>
<td>core speed</td>
</tr>
<tr>
<td>P25</td>
<td>low pressure compressor exit total pressure</td>
</tr>
<tr>
<td>T25</td>
<td>low pressure compressor exit total temperature</td>
</tr>
<tr>
<td>Ps3</td>
<td>high pressure compressor exit static pressure</td>
</tr>
<tr>
<td>T35</td>
<td>high pressure compressor exit total temperature</td>
</tr>
<tr>
<td>P5</td>
<td>low pressure turbine exit total pressure</td>
</tr>
<tr>
<td>T5</td>
<td>low pressure turbine exit total temperature</td>
</tr>
</tbody>
</table>

### Actuator Commands

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wf</td>
<td>fuel flow</td>
</tr>
<tr>
<td>VSV</td>
<td>variable stator vanes</td>
</tr>
<tr>
<td>BLD25</td>
<td>station 2.5 bleed valve</td>
</tr>
</tbody>
</table>

Commercial Modular Aero-Propulsion System Simulation 40k (C-MAPSS40k)
Model-Based Gas Path Diagnostic Architecture

- Architecture Designed Based on NASA C-MAPSS40k Engine Model

### PBM Estimated Parameters

<table>
<thead>
<tr>
<th>Description</th>
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<tbody>
<tr>
<td>6 state variables (1 rotor speeds, 5 metal temperatures)</td>
</tr>
<tr>
<td>8 engine sensors (2 rotor speeds, 3 pressure and 3 temperature)</td>
</tr>
<tr>
<td>6 engine performance deterioration tuning parameters</td>
</tr>
</tbody>
</table>

### RTSTM Kalman Filter Estimated Parameters

<table>
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<tbody>
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<td>7 state variables (2 rotor speeds, 5 metal temperatures)</td>
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<td>8 engine sensors (2 rotor speeds, 3 pressure and 3 temperature)</td>
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Commercial Modular Aero-Propulsion System Simulation 40k (C-MAPSS40k)
Engine Sensors and Commands Considered in this Study

- Station 2.5 Bleed
- VSV
- 14^{th} Stg Bleed
- Wf

*T5  P5
T35  Ps3
T25* P25*
N1   N2

*Sensors unique to VIPR II tests*
## Fault Types

<table>
<thead>
<tr>
<th>Fault Index</th>
<th>Fault Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fan</td>
</tr>
<tr>
<td>2</td>
<td>Low Pressure Compressor</td>
</tr>
<tr>
<td>3</td>
<td>High Pressure Compressor</td>
</tr>
<tr>
<td>4</td>
<td>High Pressure Turbine</td>
</tr>
<tr>
<td>5</td>
<td>Low Pressure Turbine</td>
</tr>
<tr>
<td>6</td>
<td>Station 2.5 Bleed Valve</td>
</tr>
<tr>
<td>7</td>
<td>Variable Stator Vane</td>
</tr>
<tr>
<td>8</td>
<td>14th Stage Bleed Valve</td>
</tr>
</tbody>
</table>
VIPR I Baseline Results

<table>
<thead>
<tr>
<th>Gas Path Parameter</th>
<th>Sensed Measurement</th>
<th>PBM Predicted Measurement</th>
<th>RTSTM Predicted Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>WSSR</td>
<td></td>
<td></td>
<td></td>
</tr>
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</table>

Diagnosed Fault ID

- 0: No Fault
- 1: FAN
- 2: LPC
- 3: HPC
- 4: HPT
- 5: LPT
- 6: B25
- 7: VSV
- 8: B14

Anomaly Detection Threshold

Time (sec)

0 500 1000 1500 2000 2500 3000 3500 4000
VIPR I Station 2.5 Bleed Valve Fault Results

Diagnosed Fault ID

0: No Fault
1: FAN
2: LPC
3: HPC
4: HPT
5: LPT
6: B25
7: VSV
8: B14

Gas Path Parameter

WSSR

Sensed Measurement
PBM Predicted Measurement
RTSTM Predicted Measurement

WSSR Anomaly Detection Threshold

Time (sec)
VIPR II Station 2.5 Bleed Valve Fault Results

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</table>

WSSR Anomaly Detection Threshold

Diagnosed Fault ID

- 8: B14
- 7: VSV
- 6: B25
- 5: LPT
- 4: HPT
- 3: HPC
- 2: LPC
- 1: FAN
- 0: No Fault

Time (sec)
VIPR I 14th Stage Bleed Valve Fault Results

- Gas Path Parameter
- Sensed Measurement
- PBM Predicted Measurement
- RTSTM Predicted Measurement

- WSSR
- Anomaly Detection Threshold

- Diagnosed Fault ID:
  0: No Fault
  1: FAN
  2: LPC
  3: HPC
  4: HPT
  5: LPT
  6: B25
  7: VSV
  8: B14

- Time (sec)
VIPR II 14th Stage Bleed Valve Fault Results

- **Gas Path Parameter**
- **Sensed Measurement**
- **PBM Predicted Measurement**
- **RTSTM Predicted Measurement**

- **WSSR**
- **Anomaly Detection Threshold**

- **Diagnosed Fault ID**
  - 0: No Fault
  - 1: FAN
  - 2: LPC
  - 3: HPC
  - 4: HPT
  - 5: LPT
  - 6: B25
  - 7: VSV
  - 8: B14

- **Time (sec)**
Conclusion

• Architecture was found to provide reliable steady-state fault detection and isolation

• Addition of station 2.5 sensor provided fault detection at lower power settings

• Future work will include improved matching of model to engine dynamics

• The architecture’s ability to estimate deteriorated engine performance will be evaluated during the follow on VIPR III test
Acknowledgments

Research conducted under the Vehicle Systems Safety Technologies Project of NASA’s Aviation Safety Program
Backup Slides
Model-Based Gas Path Diagnostic Architecture Enhancements

- Model-based gas path diagnostic architecture designed based on NASA C-MAPSS40k model.
- Model updates were necessary due to notable mismatch between F117 engine and C-MAPSS40k model:
  - Re-trimmed piecewise linear model to match F117 engine performance
  - Updated model thermocouple dynamics

![Graph 1: Original model and polynomial curve fit through acquired steady-state data (parameter $y_a$)](image1)

![Graph 2: Original and re-trimmed PWLM (parameter $y_a$)](image2)
Measurement residuals:

\[ \tilde{y} = y - \hat{y} \]

Weighted sum of squared residuals:

\[ WSSR = \tilde{y}^T R^{-1} \tilde{y} \]

Theoretical sensor residual:

\[ \tilde{y} = Hm \]

Fault influence matrix:

\[ H_{i,j} = \begin{bmatrix} \tilde{y}_i \\ m_j \end{bmatrix} \]

Estimated fault magnitude:

\[ \hat{m}_j = \left( H_j^T R^{-1} H_j \right)^{-1} H_j^T R^{-1} \tilde{y} \]

Estimated sensor residual:

\[ \hat{\tilde{y}}_j = H_j \hat{m}_j \]

Weighted sum of squared estimated error:

\[ WSSEE_j = \left( \tilde{y} - \hat{\tilde{y}}_j \right)^T R^{-1} \left( \tilde{y} - \hat{\tilde{y}}_j \right) \]
### VIPR II Baseline Results

<table>
<thead>
<tr>
<th>Gas Path Parameter</th>
<th>Sensed Measurement</th>
<th>Performance Baseline Model Predicted Measurement</th>
<th>Real Time Self Tuning Model Predicted Measurement</th>
</tr>
</thead>
</table>

- **WSSR**

- **Anomaly Detection Threshold**

**Diagnosed Fault ID**
- 8: B14
- 7: VSV
- 6: B25
- 5: LPT
- 4: HPT
- 3: HPC
- 2: LPC
- 1: FAN
- 0: No Fault

**Time (sec)**

0  500  1000  1500  2000  2500  3000