Using Data Science to Improve Air Safety

Distribution Statement A: Approved for Public Release per AMRDEC PAO

Presented by:
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Team Lead Aerospace Engineer
U.S. Army Aviation and Missile Research, Development, and Engineering Center

13 SEP 17
Background

• US Army Aviation Engineering Directorate
  – Airworthiness Authority for the Army
  – TRL 7-9 Development and Qualification

• Dynamics Branch
  – Health and Usage Monitoring Systems and Aviation Data Science Team Lead

• Bachelor and Master of Science in Mechanical Engineering
  – Dynamics & Modal Analysis
  – I’m not a
    • Researcher
    • Statistician or
    • Data scientist
Who is AMRDEC?

U.S. Army Aviation and Missile Research, Development, and Engineering Center provides increased responsiveness to the nation's Warfighters through aviation and missile capabilities and life cycle engineering solutions.

- Headquartered at Redstone Arsenal, AL
- 5 Directorates
- 9,000 scientists & engineers
- $2.45 billion in reimbursable funding, FY 16
- $339 million in Science & Technology funding, FY 16

AMRDEC Priorities

Strategic Readiness – provide aviation and weapons technology and systems solutions to ensure victory on the battlefield

Future Force – develop and mature Science and Technology to provide technical capability to our Army’s (and nation’s) aviation and weapons systems

Soldiers & People – develop the engineering talent to support both Science and Technology and materiel enterprise
• Health and Usage Monitoring Systems (HUMS)
  – The child of FOQA (Flight Operations Quality Assurance)

• **True Positive**: Sensitivity; HUMS correctly identified a faulted state
  – **False Negative**: Missed Detection

• **True Negative**: Specificity; HUMS correctly identified a healthy state
  – **False Positive**: False Alarm

• **Bookmakers Informedness** = TPR – FPR

• **Ground Truth**
  – Assets and Examples

• **ROC**: Receiver Operating Characteristic

• **Epicyclic Transmission**: Planetary Gearbox
What is HUMS?

Health and Usage Monitoring System

Flight Operations Data (Parametric Data)
  e.g. altitude, pitch rate, engine torque

Sensor Data
  Burst data (High Frequency)
  e.g. accelerometers
  Continuous data (Low Frequency)
  e.g. oil debris monitor
What do we use it for?

- Univariate exceedance monitoring during flight
  - Oil debris monitoring

- Health/Usage monitoring
  - Drive train vibration
  - Rotor vibration
  - Flight regime classification

- Accident Investigation
  - Cockpit voice
  - Flight data recording
Problems with HUMS?

Exclusively uses univariate exceedance classification methods which are often prone to a False Positive/Negative problem.

- The problem is temporal
- The variables are noisy
- Health is often relative
- Anomalous does not always mean broken or dangerous
- It does not account for other flight variables
The aircraft is not separated from the fleet

~50 hours prior to chip light
Case Study: Transmission Internal Failure

Epicyclic Transmission

Spiral Bevel Transmission
Can vibration transfer across an epicyclic transmission?
### How well are we actually doing?

<table>
<thead>
<tr>
<th>Epicyclic Transmission 1</th>
<th>HUMS Indicated Healthy</th>
<th>HUMS Indicated Fault</th>
<th>Assets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Condition: Healthy</td>
<td>TN=100%</td>
<td>FP=0%</td>
<td>2</td>
</tr>
<tr>
<td>Actual Condition: Faulty</td>
<td>FN=100%</td>
<td>TP=0%</td>
<td>6</td>
</tr>
<tr>
<td><strong>Sum of Assets:</strong></td>
<td></td>
<td></td>
<td><strong>8</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Epicyclic Transmission 2</th>
<th>HUMS Indicated Healthy</th>
<th>HUMS Indicated Fault</th>
<th>Assets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Condition: Healthy</td>
<td>TN=100%</td>
<td>FP=0%</td>
<td>4</td>
</tr>
<tr>
<td>Actual Condition: Faulty</td>
<td>FN=100%</td>
<td>TP=0%</td>
<td>4</td>
</tr>
<tr>
<td><strong>Sum of Assets:</strong></td>
<td></td>
<td></td>
<td><strong>8</strong></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Epicyclic Transmission 3</th>
<th>HUMS Indicated Healthy</th>
<th>HUMS Indicated Fault</th>
<th>Assets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Condition: Healthy</td>
<td>TN=0%</td>
<td>FP=100%</td>
<td>1</td>
</tr>
<tr>
<td>Actual Condition: Faulty</td>
<td>FN=100%</td>
<td>TP=0%</td>
<td>25</td>
</tr>
<tr>
<td><strong>Sum of Assets:</strong></td>
<td></td>
<td></td>
<td><strong>26</strong></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Epicyclic Transmission 4</th>
<th>HUMS Indicated Healthy</th>
<th>HUMS Indicated Fault</th>
<th>Assets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Condition: Healthy</td>
<td>TN=91%</td>
<td>FP=9%</td>
<td>11</td>
</tr>
<tr>
<td>Actual Condition: Faulty</td>
<td>FN=95%</td>
<td>TP=5%</td>
<td>21</td>
</tr>
<tr>
<td><strong>Sum of Assets:</strong></td>
<td></td>
<td></td>
<td><strong>32</strong></td>
</tr>
</tbody>
</table>
## Can we improve?

<table>
<thead>
<tr>
<th>Epicyclic Transmission 3 Built In HUMS</th>
<th>HUMS Indicated Healthy</th>
<th>HUMS Indicated Fault</th>
<th>Assets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Condition: Healthy</td>
<td>TN=0%</td>
<td>FP=100%</td>
<td>1</td>
</tr>
<tr>
<td>Actual Condition: Faulty</td>
<td>FN=100%</td>
<td>TP=0%</td>
<td>25</td>
</tr>
<tr>
<td><strong>Sum of Assets:</strong></td>
<td></td>
<td></td>
<td><strong>26</strong></td>
</tr>
</tbody>
</table>

### Modified HUMS

<table>
<thead>
<tr>
<th>Epicyclic Transmission 3 Modified HUMS</th>
<th>HUMS Indicated Healthy</th>
<th>HUMS Indicated Fault</th>
<th>Assets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Condition: Healthy</td>
<td>TN=100%</td>
<td>FP=0%</td>
<td>1</td>
</tr>
<tr>
<td>Actual Condition: Faulty</td>
<td>FN=56%</td>
<td>TP=44%</td>
<td>25</td>
</tr>
<tr>
<td><strong>Sum of Assets:</strong></td>
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<td></td>
<td><strong>26</strong></td>
</tr>
</tbody>
</table>
What about spiral bevel transmissions?

<table>
<thead>
<tr>
<th>Tail Gearbox 1</th>
<th>HUMS Indicated Healthy</th>
<th>HUMS Indicated Fault</th>
<th>Assets</th>
</tr>
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<td>Actual Condition: Healthy</td>
<td>TN=100%</td>
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<td>4</td>
</tr>
<tr>
<td>Actual Condition: Faulty</td>
<td>FN=0%</td>
<td>TP=100%</td>
<td>3</td>
</tr>
</tbody>
</table>

Sum of Assets: 7

<table>
<thead>
<tr>
<th>Tail Gearbox 2</th>
<th>HUMS Indicated Healthy</th>
<th>HUMS Indicated Fault</th>
<th>Assets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Healthy Condition:</td>
<td>TN=71%</td>
<td>FP=29%</td>
<td>7</td>
</tr>
<tr>
<td>Actual Faulty Condition:</td>
<td>FN=13%</td>
<td>TP=87%</td>
<td>15</td>
</tr>
</tbody>
</table>

Sum of Assets: 22
What are we doing to fix the problem?

Remember the Emergency Medical Hologram?
What are we doing to fix the problem?

Remember the Emergency Medical Hologram?

Please state the nature of the medical emergency
What are we doing to fix the problem?

Remember the Emergency Medical Hologram?

Please state the nature of the **engineering** emergency
We live in a common place with other industries when we talk about this topic:

- Medicine
- Nuclear Power
- Aviation

Development of multivariate machine learned diagnostics and prognostics requires a process…
This is your machine learning system?

Yup! You pour the data into this big pile of linear algebra, then collect the answers on the other side.

What if the answers are wrong?

Just stir the pile until they start looking right.
Our Machine Learning Axioms for Aviation

- Stirring the pile, is training
- Model evaluation, is training
- Model selection, is training
- Model validation, is training
- Looking under the hood, is training
- Stirring stops prior to testing
- Testing is done by the customer on a clean dataset
• We put together a general path forward we expect to see when we take on a machine learning task.

• Demonstrated in our NGB internal failure classification work
  – Cleanse
  – Partition
  – Train
  – Validate
  – Select
  – Test
  – Deploy

• We built a flow chart!
Aviation Machine Learning Process

Curation
- Curate and Clean Data
- Generate Problem Statement and Identify Available Data
- Define Airworthiness Requirements

Partitioning
- Partition the data into: Training – Validation – Testing

Training
- Train Models
- Consider new development process
- Modifications to Data or Tools required?

Validation
- Determine Best Model

Selection
- Final Training Opportunity for Best Model

Testing
- Testing and Delivery of Final Model
- Evaluate Performance in the field
- Is diagnostic performing?

Deployment and Evaluation
- Deploy and Evaluate

Modifications to Data or Tools required?
- Sufficient assets and labeled data to proceed?

Define the Model Space
Aviation Machine Learning Process

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What people think when I say machine learning
Aviation Machine Learning Process

What I’ve realized is the important part of machine learning ...

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Testing and Delivery of Final Model

Deploy and Evaluate
- Deploy and Evaluate

Consider new development process

Evaluate Performance in the field

Is diagnostic performing?

Generate Problem Statement and Identify Available Data

Define Airworthiness Requirements

Define the Model Space

Sufficient assets and labeled data to proceed?
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Is diagnostic performing?
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Aviation Machine Learning Process

- **Curation**
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- **Partitioning**
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- **Training**
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- **Deploy and Evaluate**
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Final Training Opportunity for Best Model

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Evaluate Performance in the field

Consider new development process
METRICS

Description: Bagged Logistic Regression over history-max plus FRF-CI's
Justification for inclusion in pretest: "Simplest" model on generalization (CV informedness) list

<table>
<thead>
<tr>
<th>Metric</th>
<th>Train</th>
<th>CV</th>
<th>Pretest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement Informedness</td>
<td>0.812</td>
<td>0.856</td>
<td>0.596</td>
</tr>
<tr>
<td>Measurement TPR</td>
<td>0.860</td>
<td>—</td>
<td>0.618</td>
</tr>
<tr>
<td>Asset TPR</td>
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<td>—</td>
<td>0.286</td>
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<tr>
<td>Asset FPR</td>
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<td>0.147</td>
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<td>Asset TPR (M oo N)</td>
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<td>0.429</td>
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<td>Asset FPR (M oo N)</td>
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<tr>
<td>Asset Unpredicted Negatives</td>
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<td>—</td>
<td>0.004</td>
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<tr>
<td>Asset MooN Unpredicted Positives</td>
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<td>—</td>
<td>0.125</td>
</tr>
<tr>
<td>Asset MooN Unpredicted Negatives</td>
<td>0.000</td>
<td>—</td>
<td>0.004</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Training</th>
<th>Real Positives</th>
<th>Real Negatives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted Positives</td>
<td>313.0</td>
<td>674.0</td>
</tr>
<tr>
<td>Predicted Negatives</td>
<td>51.0</td>
<td>13528.0</td>
</tr>
</tbody>
</table>
ROC curves

ROC curves for different conditions:
- Training
- Pretest
- Test
Temporal Assessment of Performance

One year of historical predictions, ending at removal

Truth at removal  Prediction ratio
RandomizedPCA on STA:64D-NX-SF-NX-10

<table>
<thead>
<tr>
<th>Unsupervised model parameters</th>
<th>Data attributes</th>
<th>before</th>
<th>after</th>
</tr>
</thead>
<tbody>
<tr>
<td>n_components</td>
<td>n_rows</td>
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<td>14566</td>
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<tr>
<td></td>
<td>n_features</td>
<td>128</td>
<td>15</td>
</tr>
</tbody>
</table>
How did it perform in cross validation?

**CROSS-VALIDATION w/ 10 FOLDS**

<table>
<thead>
<tr>
<th>Fold #</th>
<th>True Positive Rate</th>
<th>False Positive Rate</th>
<th>True Positive Accuracy</th>
<th>True Negative Accuracy</th>
<th>Informedness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fold #0</td>
<td>1.00</td>
<td>0.00</td>
<td>0.22</td>
<td>1.00</td>
<td>0.92</td>
</tr>
<tr>
<td>Fold #1</td>
<td>0.84</td>
<td>0.06</td>
<td>0.26</td>
<td>1.00</td>
<td>0.78</td>
</tr>
<tr>
<td>Fold #2</td>
<td>0.00</td>
<td>0.02</td>
<td>0.30</td>
<td>1.00</td>
<td>0.87</td>
</tr>
<tr>
<td>Fold #3</td>
<td>1.00</td>
<td>0.00</td>
<td>0.34</td>
<td>1.00</td>
<td>0.94</td>
</tr>
<tr>
<td>Fold #4</td>
<td>1.00</td>
<td>0.07</td>
<td>0.23</td>
<td>1.00</td>
<td>0.93</td>
</tr>
<tr>
<td>Fold #5</td>
<td>0.98</td>
<td>0.07</td>
<td>0.24</td>
<td>1.00</td>
<td>0.92</td>
</tr>
<tr>
<td>Fold #6</td>
<td>1.00</td>
<td>0.06</td>
<td>0.29</td>
<td>1.00</td>
<td>0.94</td>
</tr>
<tr>
<td>Fold #7</td>
<td>0.90</td>
<td>0.02</td>
<td>0.55</td>
<td>1.00</td>
<td>0.82</td>
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<tr>
<td>Fold #8</td>
<td>0.99</td>
<td>0.03</td>
<td>0.49</td>
<td>1.00</td>
<td>0.90</td>
</tr>
<tr>
<td>Fold #9</td>
<td>0.82</td>
<td>0.02</td>
<td>0.52</td>
<td>0.99</td>
<td>0.79</td>
</tr>
</tbody>
</table>
HUMS_OMNI as of 09/04/17

Generated by the Aviation Engineering Directorate
Aeromechanics Division

| 48/56  | 23 Aug |
| 02/12  | 26 Aug |
| 01/39  | 08 Aug |
| 03/03  | 11 Jul |
| 04/19  | 28 Aug |
| 06/83  | 25 Aug |
| 02/10  | 03 Aug |
| 19/19  | 19 Jul |
| 07/13  | 01 Aug |
• Yes, but it needs some adjustments:
  – Metrics need to be computed across the maximum data for the life of the aircraft
    • Sampling techniques are ok for training but not when reporting performance
  – Post Mortem indicates we picked almost the best choice but not the best choice
    • We could have an improvement of up to 10% informedness

• Does it automate away the engineer?
  – No, but it sure does give them a great place to focus
    • 650 aircraft and you have confidence that you will be focused on the select 9 or 10 that need your attention
    • Still has a FP rate that needs engineering assistance
This is a team effort

Thanks to the great government and contractor team:

- AMRDEC
  - Andrew
  - Jeremy
  - Matt
  - Jamie
- Avion
  - Shawn
- PEO-AVN
  - Frances
- Avion
  - Andrew
  - Abe
  - Raj
- RMCI
  - Lance
  - Nate
  - Steve


• Cal Tech: “Learning From Data”
  – **FREE** on YouTube
  – [https://work.caltech.edu/telecourse](https://work.caltech.edu/telecourse)

• NASA work in Flight Operations Data and the Future ATC System
  – [https://www.nasa.gov/content/air-traffic-operations-lab-answering-big-questions-about-the-future-of-air-travel](https://www.nasa.gov/content/air-traffic-operations-lab-answering-big-questions-about-the-future-of-air-travel)

• Journal of Aerospace Information Systems
  – [https://arc.aiaa.org/loi/jais](https://arc.aiaa.org/loi/jais)

• SIGKDD (Association for Computing Machinery: Special Interest Group on Knowledge Discovery and Data Mining)

• ASME V&V Symposium
  – [https://www.asme.org/events/vandv](https://www.asme.org/events/vandv)
Upcoming Events
AIRWORTHINESS, CBM, and HUMS Technical Meeting
Call for Papers
Feb. 20-22, 2018 — Huntsville, AL

The Redstone Chapter of AHS International will be sponsoring a Technical Meeting on Airworthiness, Condition Based Maintenance (CBM), and Health and Usage Monitoring (HUMS) on February 20-22, 2018 in Huntsville, Alabama. The Technical Meeting will present applicable technologies that are new to continued airworthiness, current and potential processes, and hardware required for military and civil aircraft airworthiness.

Abstracts are to be submitted to abstracts@ahsredstone.org no later than October 13, 2017. It is strongly encouraged that abstracts be submitted in a .pdf format and not be any larger than 2MB. They should be approximately 1,000 words, present the status of the background data to be used, summarize figures and illustrations to be used (with samples), and include a summary of important conclusions. Abstracts will be accepted in a variety of technical disciplines related to commercial or military aircraft Airworthiness, Condition Based maintenance, Health-Monitoring Technologies, or Certification Qualification of vertical flight aircraft. Papers are solicited on the following topics:

- HUMS/SUMS for maintenance credits
- Measuring the Return on Investment of HUMS installation, analysis, and data retention
- Using HUMS to improve logistics and decrease aircraft downtime
- Low-cost HUMS solutions
- Improvement of data flow on and off board aircraft
- Civil and Military Regulatory Advancements and Recommendations related to HUMS
- Flight Data Analysis (FOQA/FDM)
- Aviation Data science
- Next Generation HUMS
- HUMS sensors, architecture improvements, and technologies
- MHS/APR, Pilot, and Operator experiences and feedback
- Using HUMS to influence Future Vertical Lift design
- Fault Modeling and Simulation for HUMS development and qualification

Redstone Arsenal
Data Science Working Group
Open Announcement and Call for Participation

Pockets of engineers and analysts across Redstone Arsenal are applying data science methods to government data. Many of these groups may have common problems even though they have different datasets.

How do we leverage existing knowledge and parallel efforts to improve efficiency and maximize capability? If you think you may fall into this category, join us!

This free event is cosponsored by AMRDEC and MSIC. The planned format is a single auditorium with short talks and panel discussions. We are soliciting interested individuals to participate in this event through submission of short abstracts for talks or panels as related to the listed topics.

If you are interested in this event, please submit your abstracts or questions to the listed organizers. Agenda and attendance information is forthcoming.

This event is unclassified and is intended for government employees and government sponsored onsite support contractors only. Please contact a POC below for detailed information.

Join us!
7 November 2017
MSIC Auditorium
Thank you for your time and attention
AMRDEC Web Site
www.amrdec.army.mil

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www.facebook.com/rdecom.amrdec

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