Abnormal Derivative Frequency for Sensor and Wiring Prognostics

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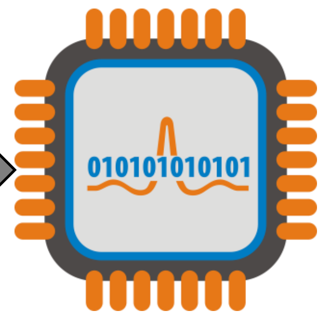
Motivation

Challenge: Detect the *onset* of sensor/wiring problems

How sensor/wiring problems are typically detected

Rotorcraft Platform

Sensor signals



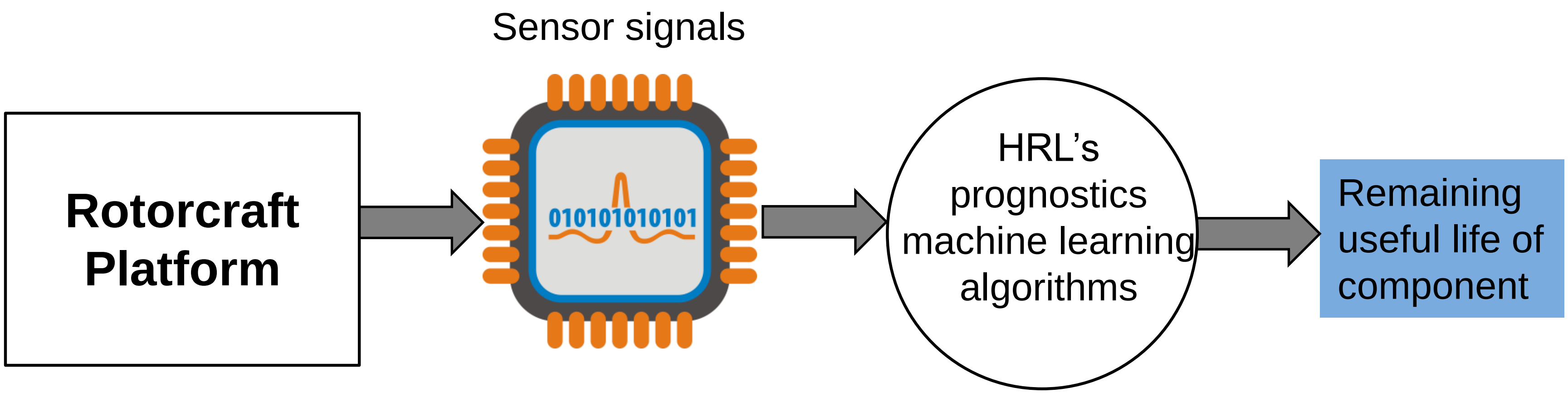
Signal outside pre-defined range

Rotorcraft Maintenance Operation

Pilot or maintenance personnel detect failure and fix the problem

Motivation

Challenge: Transient early warning signals (EWS) that *do not* trigger fault messages



What caused erroneous predictions?

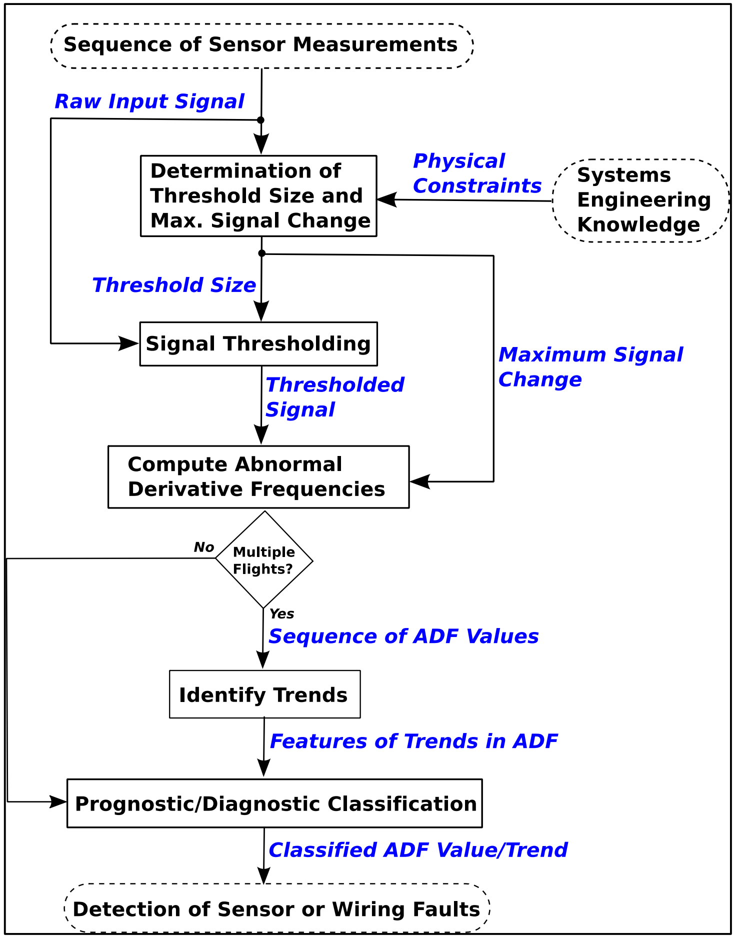
Hidden sensor/wiring anomalies

Methods: Abnormal Derivative Frequency

Insight: For these EWS, signal *derivative* is more important than signal value

Signal derivatives

Abnormal Derivative Frequency (ADF) algorithm



Methods: Abnormal Derivative Frequency

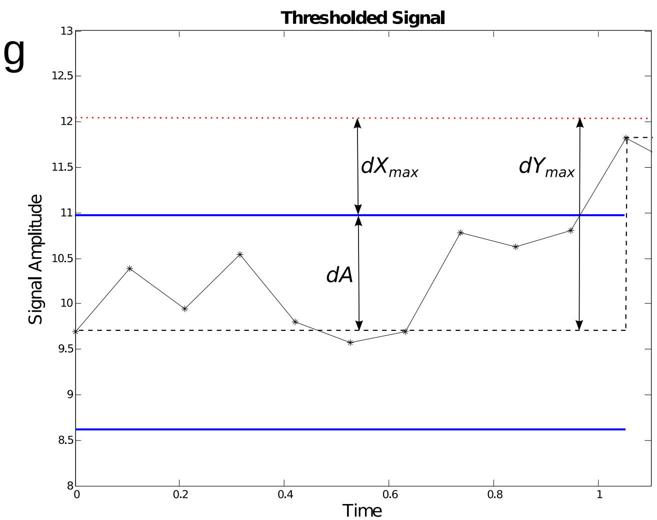
Definitions of the ADF

1) ADF = $N_{abnormal}/N_{total}$

2) ADF = $N_{abnormal}$/hour

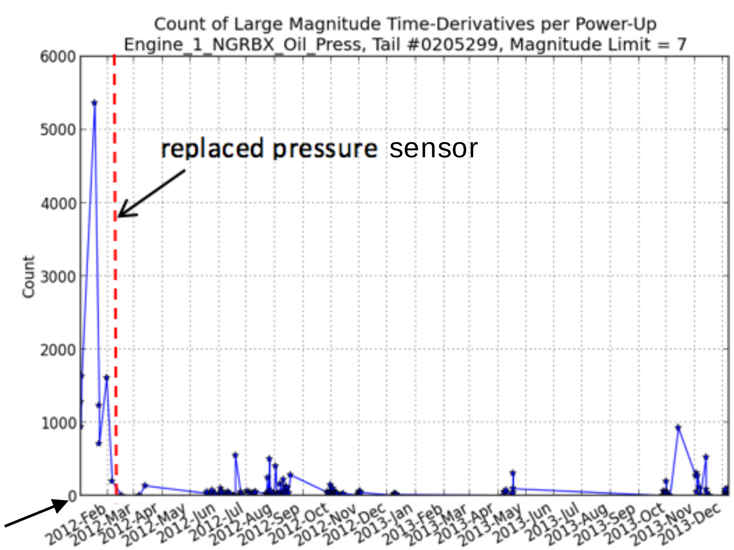
- $N_{abnormal}$ is number of 1-step derivatives with abnormally large value
- N_{total} total is number of non-zero 1-step derivatives (# changes)
- One ADF value per power-up/flight

Illustration of thresholding scheme used in Apache sensor data



Example Case Study

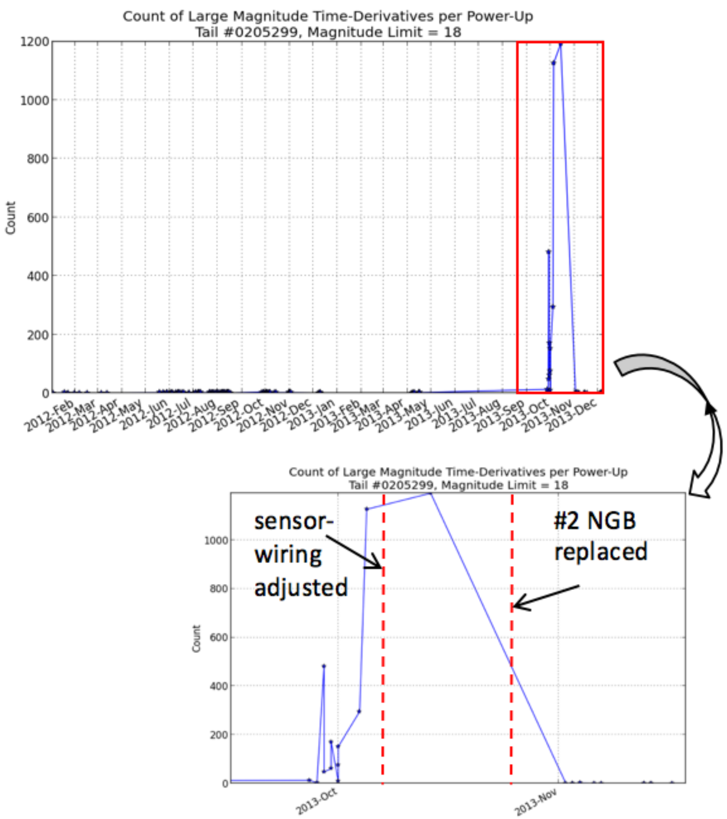
- Nose gearbox #1 (NGB 1) oil pressure
- Magnitude limit = 7psi
- Each point corresponds to a single flight
- *ADF detects problem >1.5 months before fix*



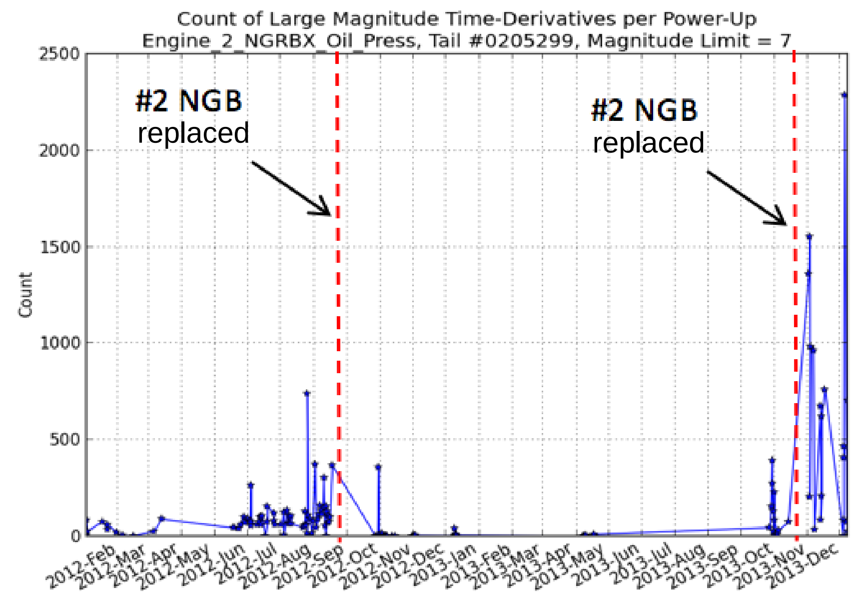
Sensor problems detected

Results: Two Drive System Case Studies

- Nose gearbox #2 (NGB 2) oil temperature
- Magnitude limit = 18psi
- *ADF detects progression to failure*
- *Wiring adjustment did not fix the problem*



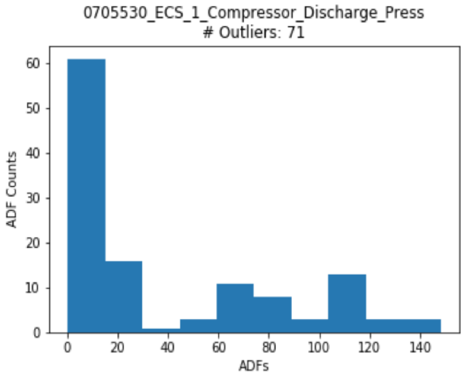
- Nose gearbox #2 oil pressure
- Magnitude limit = 7psi
- *ADF detects problems ~3 months before 1st failure*
- *ADF detects problems introduced by 2nd NGB 2 replacement (no fault messages)*

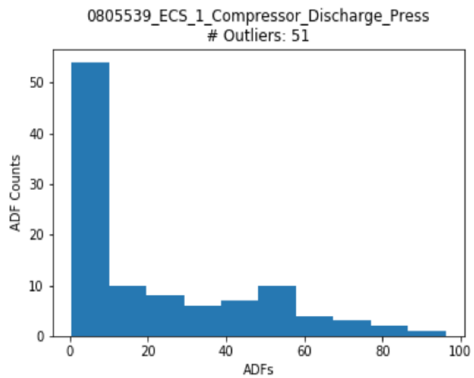


Results: Environmental Control System

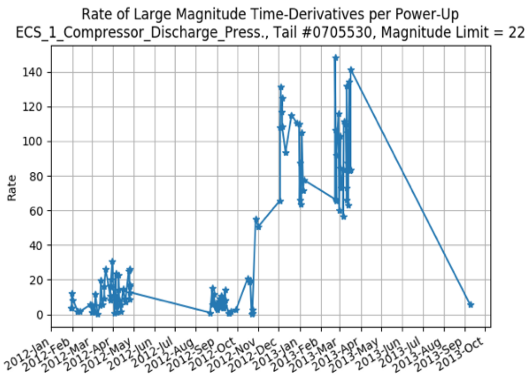
- ADF statistics for 100+ flights from each of two tails
  - Compressor discharge pressure
  - Magnitude limit = 22psi
- Histograms show many flights with large ADF values (e.g., ADF > 10)
- Time-series plots show problems persisting for many months/flights
  - No fault messages issued

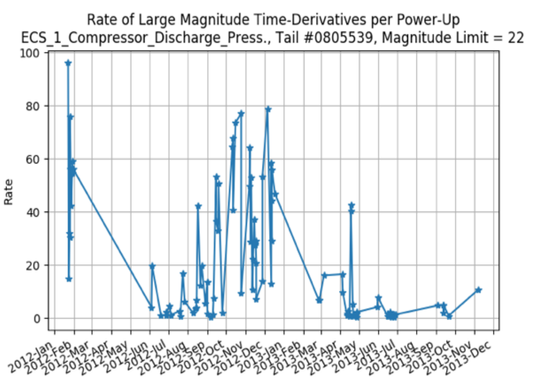
Histogram of ADFs per Power-Up





Time-Series of ADFs per Power-Up





Sensor and wiring problems can persist >6 months and >50 flights!

Results: ADF Analysis of NGB Sensors/Wiring

- Computed ADF for each of 5260 flights from 79 randomly selected rotorcraft
- Focused on NGB oil temperature and pressure
- Set “alarm” threshold at ADF > 10 (abnormal/hour)
- *NGB oil pressure sensor/wiring is especially problematic*
  - For NGB 1, 24.3% of flights had “alarms”
  - For NGB 2, 41.5% of flights had “alarms”

<u>Statistics of High ADF Values for NGB Oil Pressure and Temperature</u>

Variable	# Power-Ups with ADF > 10 (abnormal/hour)
NGB 1 Oil Pressure	1279 (24.3%)
NGB 2 Oil Pressure	2182 (41.5%)
NGB 1 Oil Temperature	32 (1.0%)
NGB 2 Oil Temperature	58 (1.0%)

Results: ADF Analysis of ECS Sensors/Wiring

- Computed ADF for each of 3534 flights from 49 randomly selected rotorcraft
- Focused on sensor measurements in Environmental Control System (ECS)
- Set "alarm" threshold at ADF > 10 (abnormal/hour)
- *Compressor discharge pressure sensor/wiring is especially problematic*
  - For ECS 1, 12.0% of flights had "alarms"
  - For ECS 2, 17.4% of flights had "alarms"

<u>Statistics of High ADF Values for ECS Components</u>

Variable	# Power-Ups with ADF > 10 (abnormal/hour)
ECS 1 Compressor Discharge Pressure	423 (12.0%)
ECS 2 Compressor Discharge Pressure	615 (17.4%)
ECS 1 Compressor Suction Temperature	136 (3.8%)
ECS 2 Compressor Suction Temperature	131 (3.7%)
ECS 1 Condenser Discharge Temperature	89 (2.5%)
ECS 2 Condenser Discharge Temperature	88 (2.5%)
ECS 1 Condenser Inlet Temperature	87 (2.5%)
ECS 2 Condenser Inlet Temperature	87 (2.5%)
ECS 1 Compressor Suction Pressure	14 (0.4%)
ECS 2 Compressor Suction Pressure	17 (0.5%)

Abnormal Derivatives During Hot-Refuel Conditions

- ADF often increases when rotorcraft on ground and rotors at ~60% of max speed
- Signals appear well before serious problems develop

Increased ADF during hot-refuel

Similar condition encountered upon landing

Summary and Benefits of the ADF

- ADF is simple to compute
  - Easy to implement on a mission processor
- Detects subtle intermittent problems that do not trigger fault messages
- ADF is effective for wide range of sensor types
- Can be used as EWS input to downstream prognostics algorithms
- Detected sensor/wiring faults with 8-55 flight lead-times (1-6 months)
- Discovered NGB oil pressure sensors/wiring as highly problematic
  - 24%-42% of flights have faults
- Discovered compressor discharge pressure sensor/wiring as problematic
  - 12%-17% of flights have faults
  - Faults can last longer than 6 months and 50 flights

Future Work

- Discriminating between sensor and wiring problems
  - Wiring problem → long isolated “bursts” of large derivatives
  - Sensor problem → small clusters of large derivatives spread across a flight
- Extending analysis to E-model rotorcraft and other component types
- Quantify failure lead-times provided by ADF