Validation of Model-Based Prognostics for Pneumatic Valves in a Cryogenic Fueling Demonstration Testbed

Chetan S. Kulkarni\textsuperscript{1,3}, Matthew Daigle\textsuperscript{2}, George Gorospe\textsuperscript{3} and Kai Goebel\textsuperscript{4}

\textsuperscript{1,3} SGT Inc., NASA Ames Research Center
\textsuperscript{2} Nio
\textsuperscript{4} NASA Ames Research Center

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Motivation

- Valves are a critical element in several domains
  - For aerospace, valves are used in cryogenic fuel transfer systems
- Faults in valves can have significant effects on system performance
  - A fault in a valve in critical flow path could mean a launch scrub, costing time, money, and fuel
- Valve prognostics is needed to monitor valve health and predict when maintenance is needed before an adverse event occurs
- Testbeds are useful to inject controllable damage progression in an accelerated time frame for testing and validation of prognostics algorithms
Outline

- Valve Testbed
- Valve Modeling
- Valve Prognosis
  - Estimation
  - Prediction
- Fault Injection Results
- Conclusion and Future Work
Testbed

- Developed testbed to inject faults in pneumatic valves for cryogenic loading system
- Testbed used to validate valve prognostics algorithms
- Inject leak faults at four different locations with controllable fault progression
- Fault injection rig implemented to connect to valves Prognostics Lab at Ames and at Cryogenic Testbed System at KSC
Testbed Schematic

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Discrete Valve (DV)

- **Operation**
  - Valve is normally open
  - Return spring pushes piston up and keeps valve open
  - To close the valve, pump pneumatic gas into the pneumatic port, gas pressure overcomes spring force and pushes piston down, closing the valve
  - Valve required to open and close within given time limits, and return to fully open position upon pressure loss → These define EOL

- **Faults**
  - Leak at port (to atmosphere or from supply)
  - Return spring degradation
  - Friction increase
  - Leaks can be injected and the rate of fault progression controlled
Discrete Valve Leak Faults

Valve open time increases

Valve close time increases
Valve Modeling

- Valve state consists of valve position, valve velocity, gas masses above and below piston
- Piston movement governed by sum of forces, including
  - Friction
  - Spring force
  - Contact forces
  - Gas pressures
  - Fluid pressure
- Mass flows determined by choked and non-choked gas flow equations for orifices
- Possible sensors include position, flow, gas pressures, and open/closed indicators
Fault Modeling

• Leaks are modeled as additional flow terms
• Leaks parameterized by the size of the leak (i.e., leak hole area)
• Valve timing is changed due to leaks
  – Leak to atmosphere causes increase in time to close
  – Leak from supply causes an increase in time to open
Model-Based Architecture

1. System receives inputs, produces outputs

2. Identify active damage mechanisms

3. Estimate current state and parameter values

4. Predict EOL and RUL as probability distributions

System

Fault Detection Isolation & Identification

Estimation

Prediction

\[ u_k \] \[ y_k \] \[ F \] \[ p(x_k, \theta_k|y_{0:k}) \] \[ p(EOL_k|y_{0:k}) \] \[ p(RUL_k|y_{0:k}) \]
Problem Formulation

- Prognostics goal
  - Compute $EOL = \text{time point at which component no longer meets specified performance criteria}$
  - Compute $RUL = \text{time remaining until } EOL$

- System model
  $\dot{x}(t) = f(t, x(t), \theta(t), u(t), v(t))$
  $y(t) = h(t, x(t), \theta(t), u(t), n(t))$

- Define threshold $T_{EOL}(x(t), \theta(t))$ from performance specs that is 1 when system is considered failed, 0 otherwise

- EOL and RUL defined as
  \[
  EOL(t_P) \triangleq \inf\{t \in \mathbb{R} : t \geq t_P \land T_{EOL}(x(t), \theta(t)) = 1\}
  \]
  \[
  RUL(t_P) \triangleq EOL(t_P) - t_P
  \]

Compute $p(EOL(t_P)|y_{0:t_P})$ and/or $p(RUL(t_P)|y_{0:t_P})$
Estimation

• Only available measurement is valve position
  – Valve timing used for fault isolation, estimation, and prediction
  – Isolate the leak based on the direction of change of opening and closing times

• Physics model describes, given a leak size, the corresponding opening and closing times
  – Given observed opening and closing times, can find the leak size that produces those times
  – Simulate the model for various fault sizes to obtain a map of open and close times to corresponding fault size

- Estimated leak sizes for leak from supply (no noise)
- Estimated leak sizes for leak to atmosphere (no noise)
Prediction

- Assume leak sizes are linearly progressing with each cycle of the valve.
- Given estimated leak sizes over time, fit a linear model to the leak size growth.
- Can then determine when the leak will grow to a size that violates the opening/closing time constraints.

Predicted end of life for leak from supply (no noise)

Predicted end of life for leak to atmosphere (no noise)
Testbed: DV Leak to Atmosphere

- Proportional valve V1 injecting the fault in line opened
- At each cycle fault injection percentage increased by 1%
Leak is only observable when leak valve is opened a certain amount.
Before that time, predictions are meaningless.
Once the fault is observable, predictions converge and are fairly accurate.
Testbed: DV Leak from Supply

- Proportional valve V2 injecting the fault in line opened
- At each cycle fault injection percentage increased by 1%
Testbed: DV Leak from Supply

- Similar to atmosphere leak, fault is only observable at a certain magnitude
- Once observable, predictions begin to converge
- Closing times are unusable in this case
- Opening times flatten at end – potentially due to flow profile of leak valve
Discussion

• Studying realistic degradation phenomenon and failure effects for pneumatic valves in propellant loading systems.
• Injected controlled faults through developed hardware in-loop interface.
• Physics models to implement prognostic algorithms such that we are able to make accurate RUL and EOL predictions.
• Developed prognostic methodologies for field operations and aid crew to make effective maintenance-related decisions.
Future Work

• Testbed experiments show the weaknesses of the approach and suggest areas for improvement, and the practical issues that must be dealt with

• Future work
  – Additional experiments
  – Further validation of the approach
  – Applications to other components in propellant loading systems
THANK YOU

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