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

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Motivation

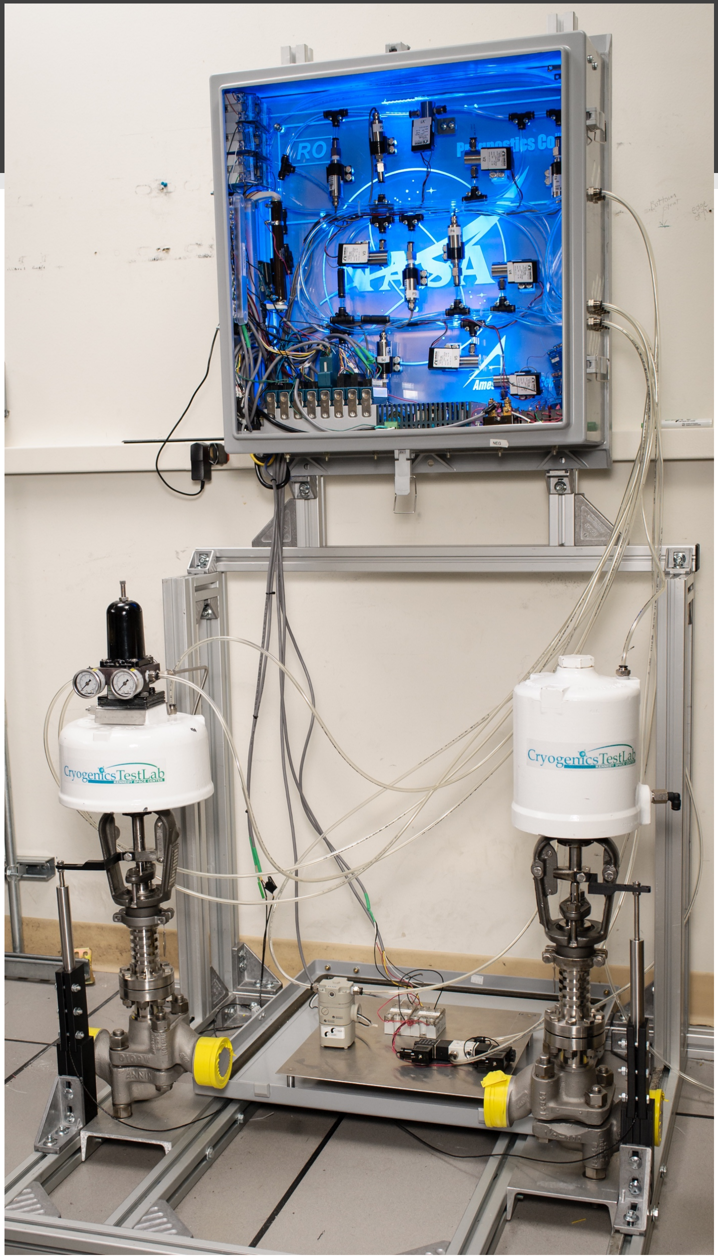
- Valves are a critical element in several domains
  - For aerospace, valves are used in cryogenic fuel transfer systems
- Faults in valves can have significant effects on system performance
  - A fault in a valve in critical flow path could mean a launch scrub, costing time, money, and fuel
- Valve 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

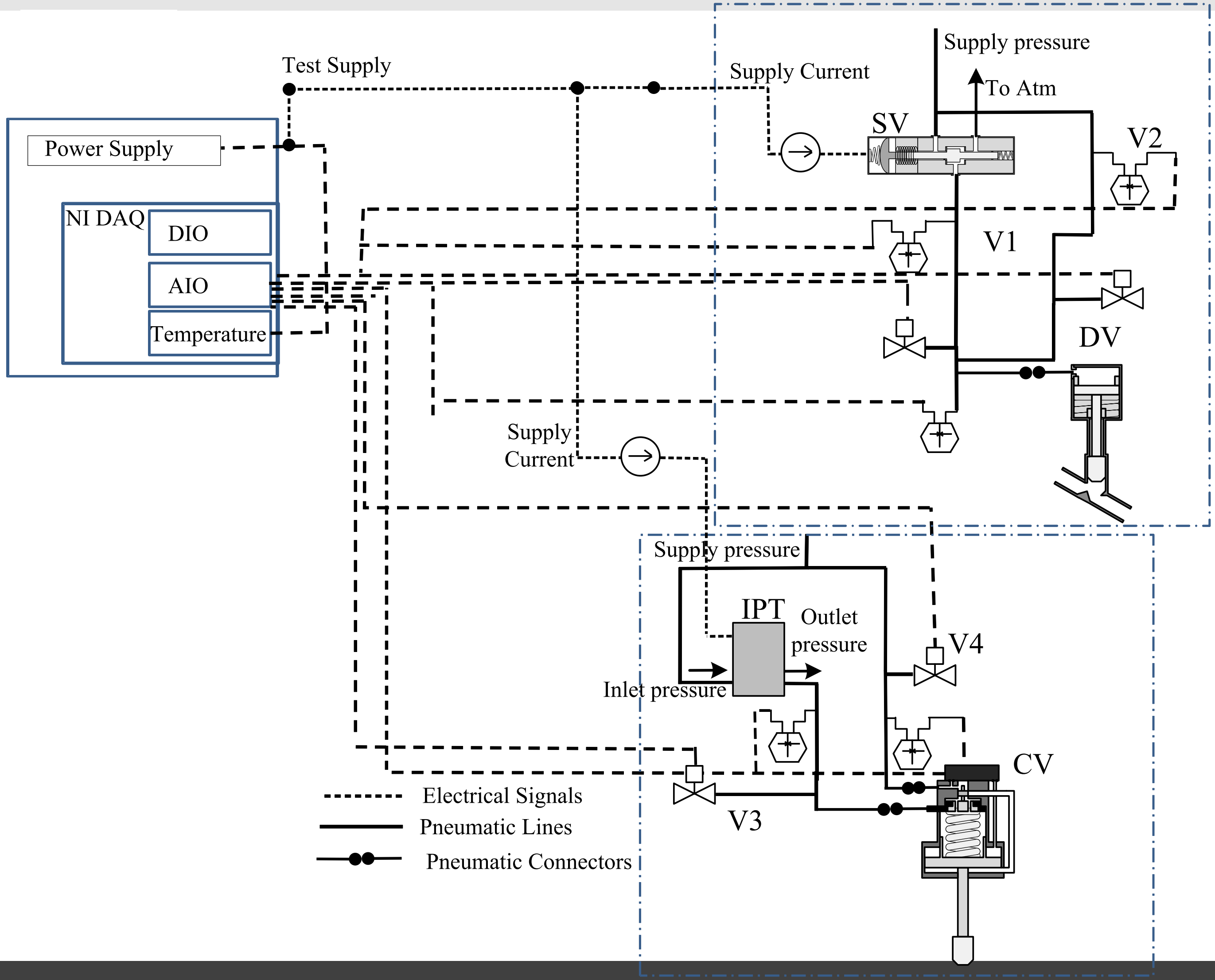
- Valve Testbed
- Valve Modeling
- Valve Prognosis
  - Estimation
  - Prediction
- Fault Injection Results
- Conclusion and Future Work

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

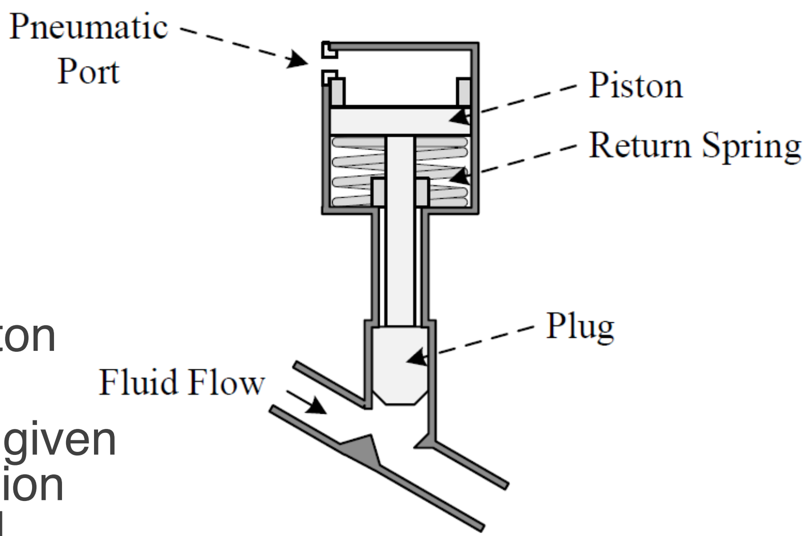


Testbed Schematic



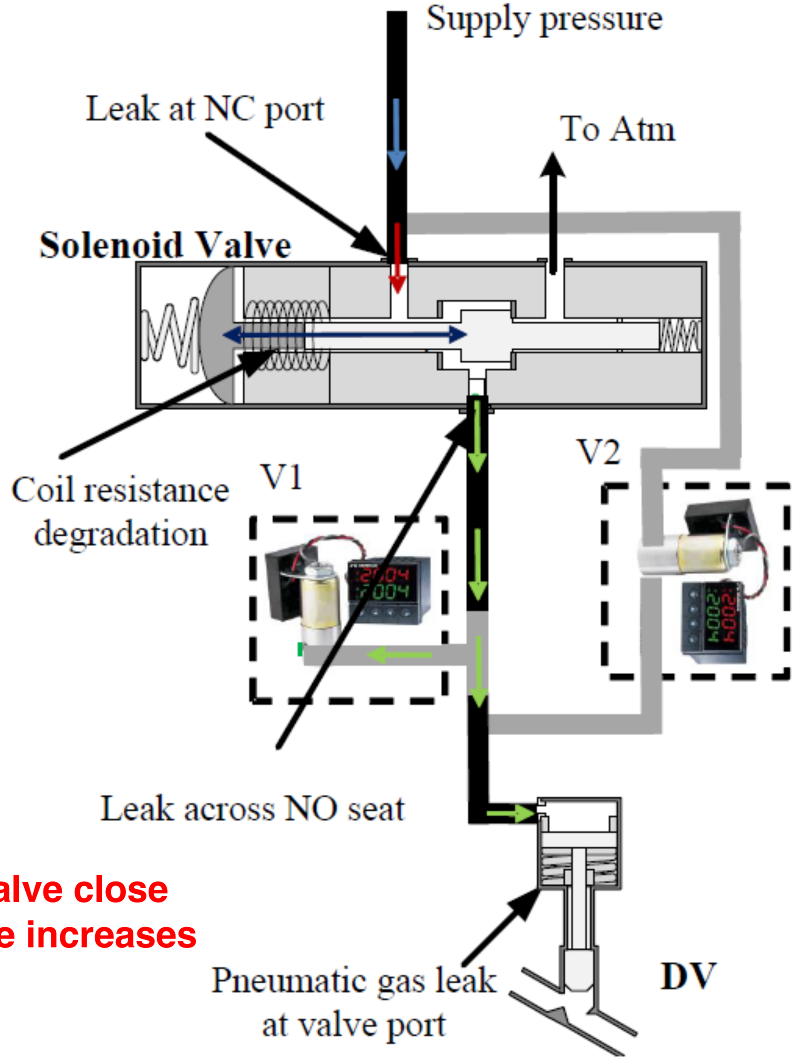
Discrete Valve (DV)

- 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

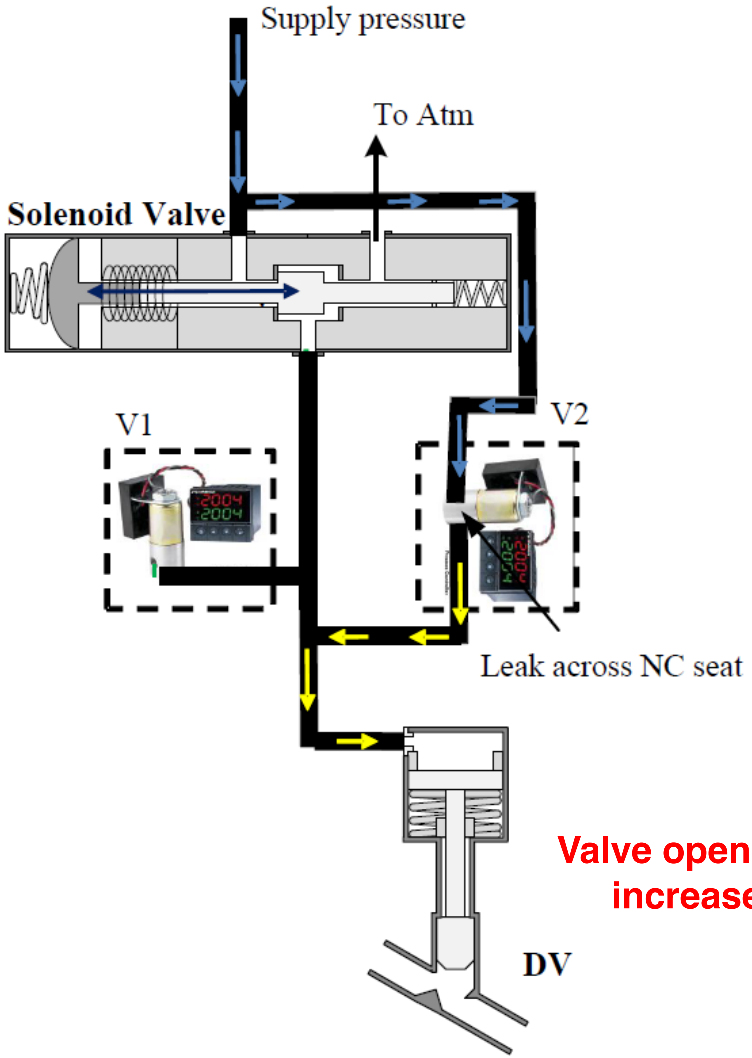


- Faults
  - Leak at port (to atmosphere or from supply)
  - Return spring degradation
  - Friction increase
  - Leaks can be injected and the rate of fault progression controlled

Discrete Valve Leak Faults



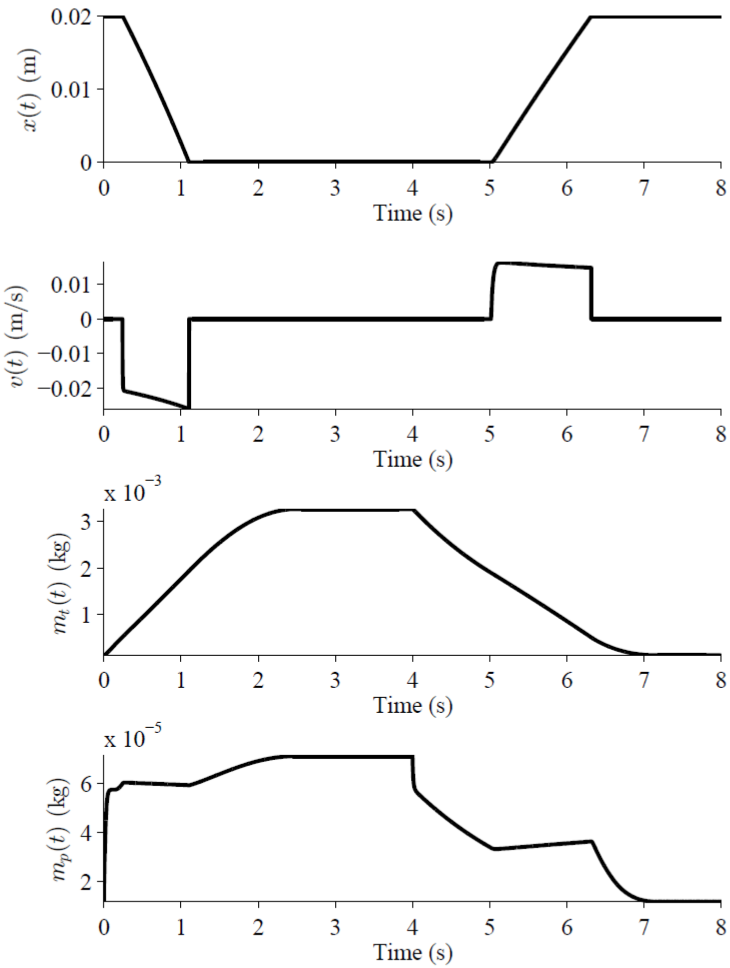
Valve close time increases



Valve open time increases

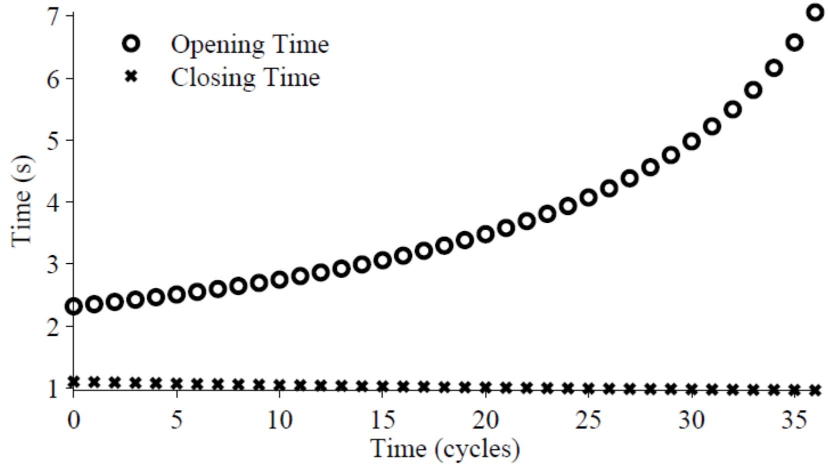
Valve Modeling

- 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

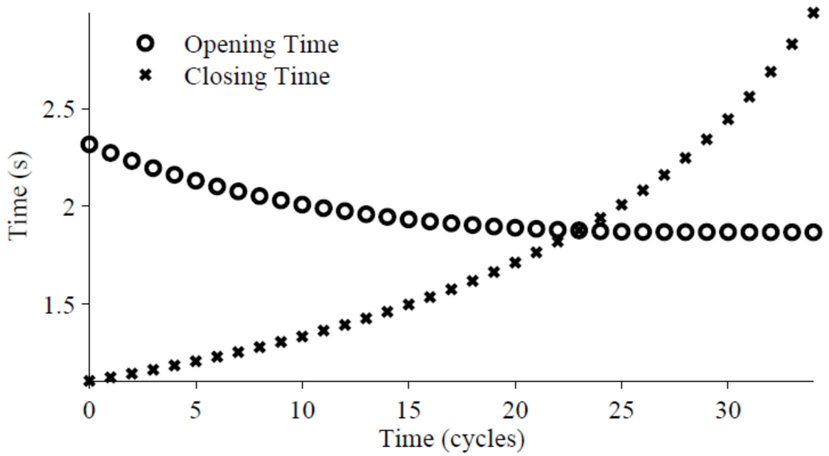


Fault Modeling

- 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



Valve timing with leak from supply

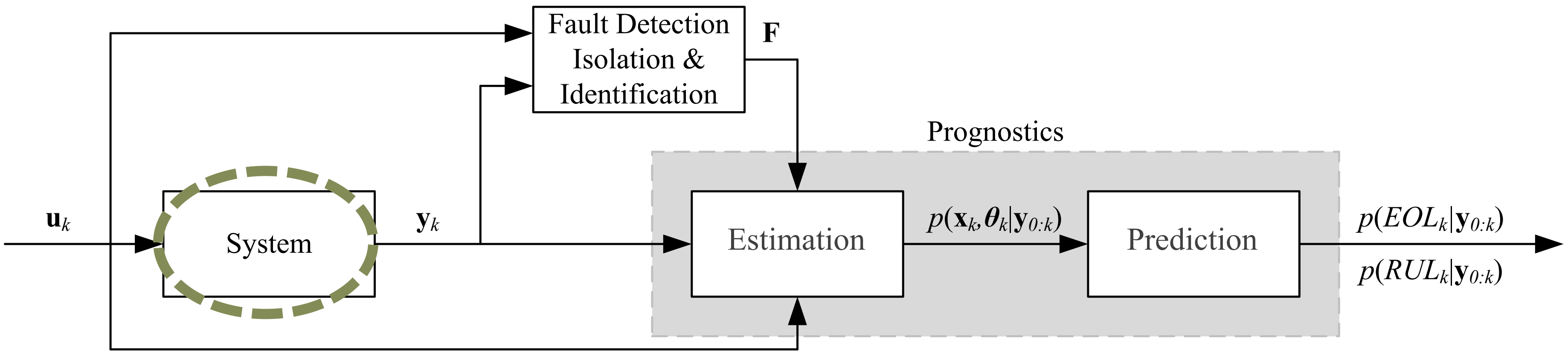


Valve timing with leak to atmosphere

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

Problem Formulation

- Prognostics goal
  - Compute EOL = time point at which component no longer meets specified performance criteria
  - Compute RUL = time remaining until EOL
- System model

State Parameters Input Process Noise

$$\begin{aligned}\dot{\mathbf{x}}(t) &= \mathbf{f}(t, \mathbf{x}(t), \boldsymbol{\theta}(t), \mathbf{u}(t), \mathbf{v}(t)) \\ \mathbf{y}(t) &= \mathbf{h}(t, \mathbf{x}(t), \boldsymbol{\theta}(t), \mathbf{u}(t), \mathbf{n}(t))\end{aligned}$$

Output Sensor Noise

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

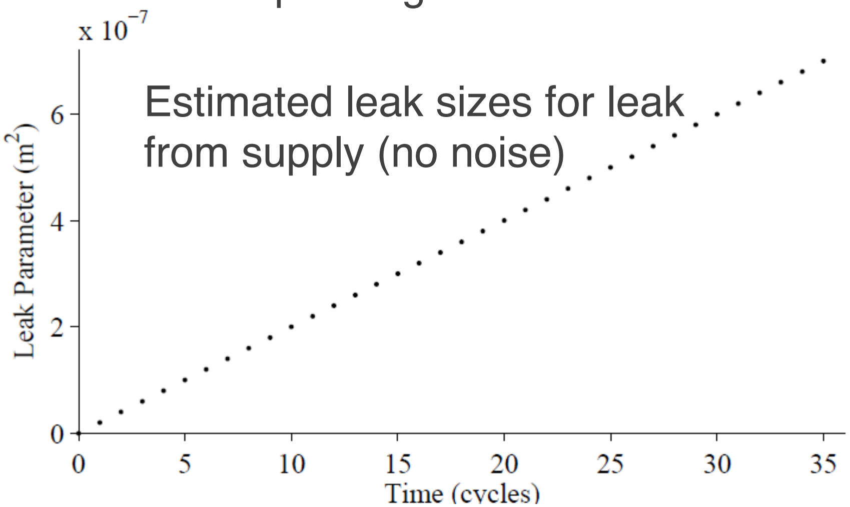
$$EOL(t_P) \triangleq \inf\{t \in \mathbb{R} : t \geq t_P \wedge T_{EOL}(\mathbf{x}(t), \boldsymbol{\theta}(t)) = 1\}$$

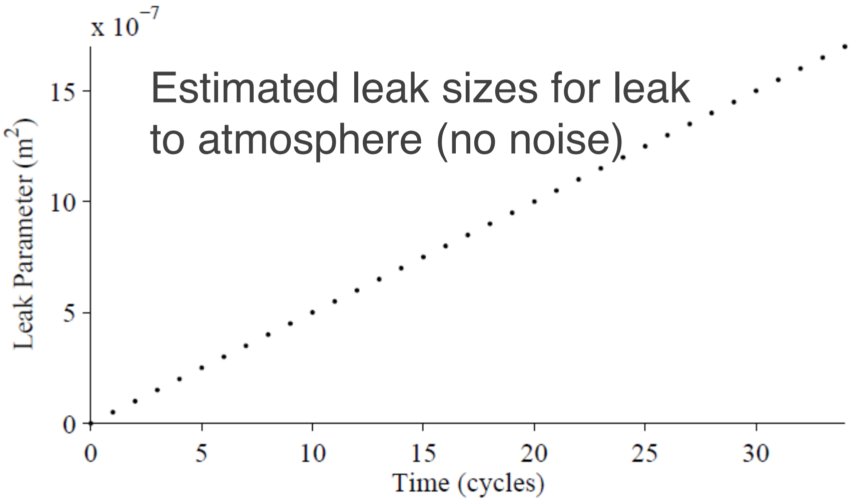
$$RUL(t_P) \triangleq EOL(t_P) - t_P$$

Compute $p(EOL(t_P)|\mathbf{y}_{0:t_P})$ and/or $p(RUL(t_P)|\mathbf{y}_{0:t_P})$

Estimation

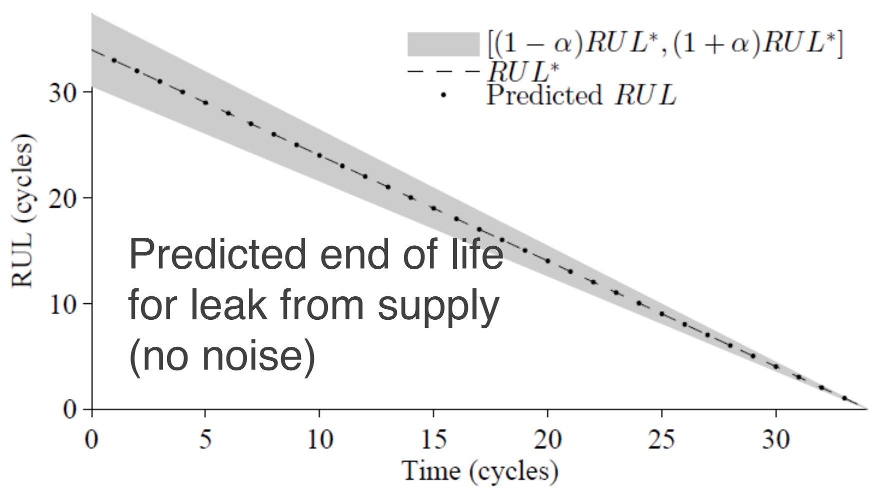
- Only available measurement is valve position
  - Valve timing used for fault isolation, estimation, and prediction
  - Isolate the leak based on the direction of change of opening and closing times
- Physics model describes, given a leak size, the corresponding opening and closing times
  - Given observed 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

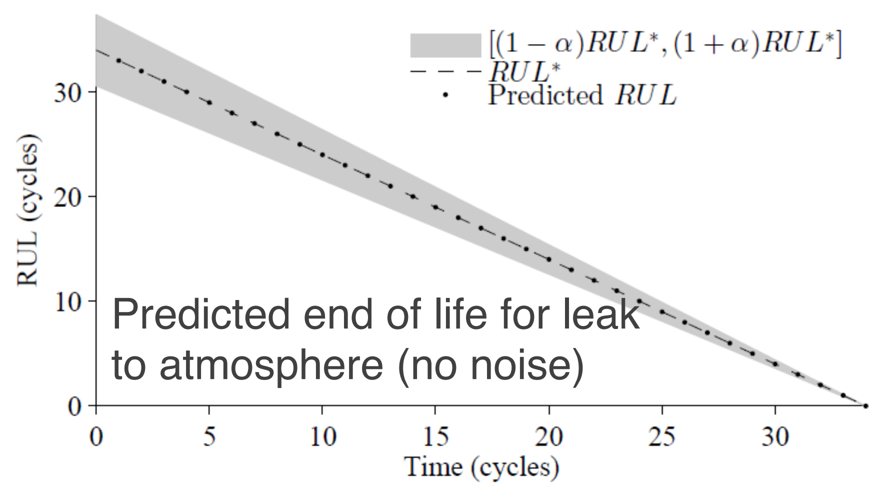




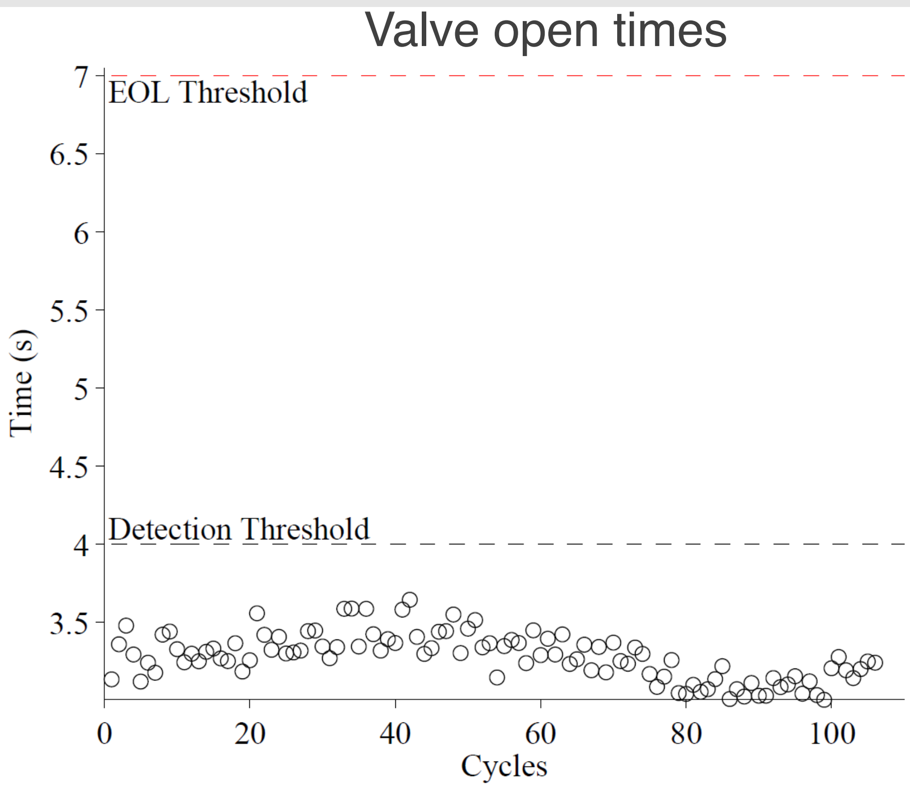
Prediction

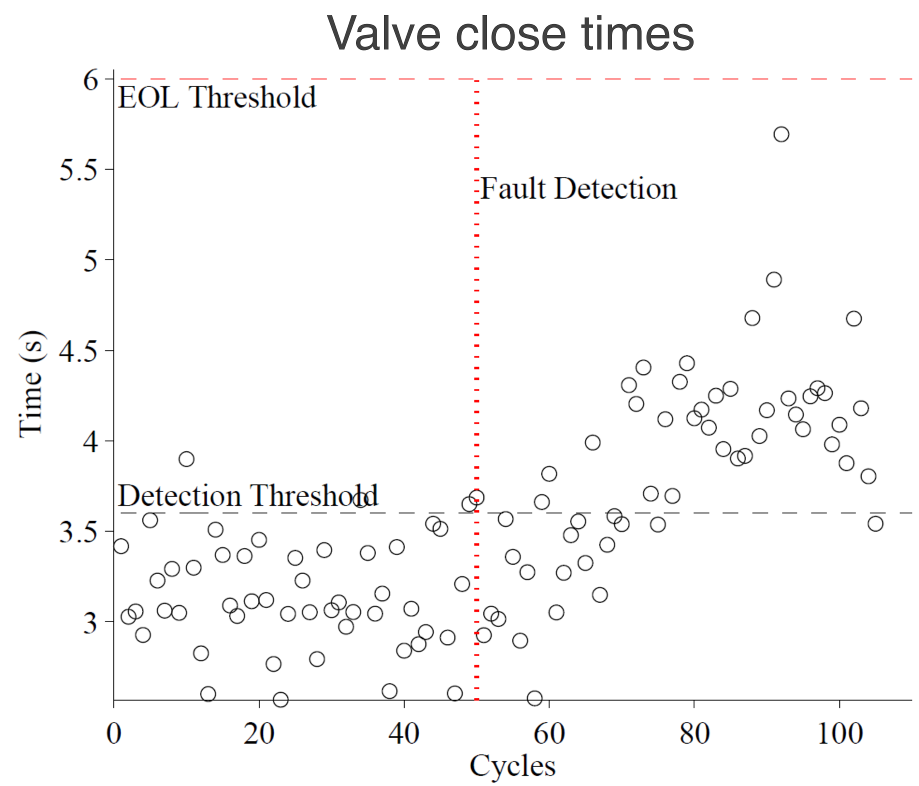
- Assume leak sizes are linearly progressing with each cycle of the valve
- Given estimated leak sizes over time, fit a linear model to the leak size growth
- Can then determine when the leak will grow to a size that violates the opening/closing time constraints





Testbed: DV Leak to Atmosphere

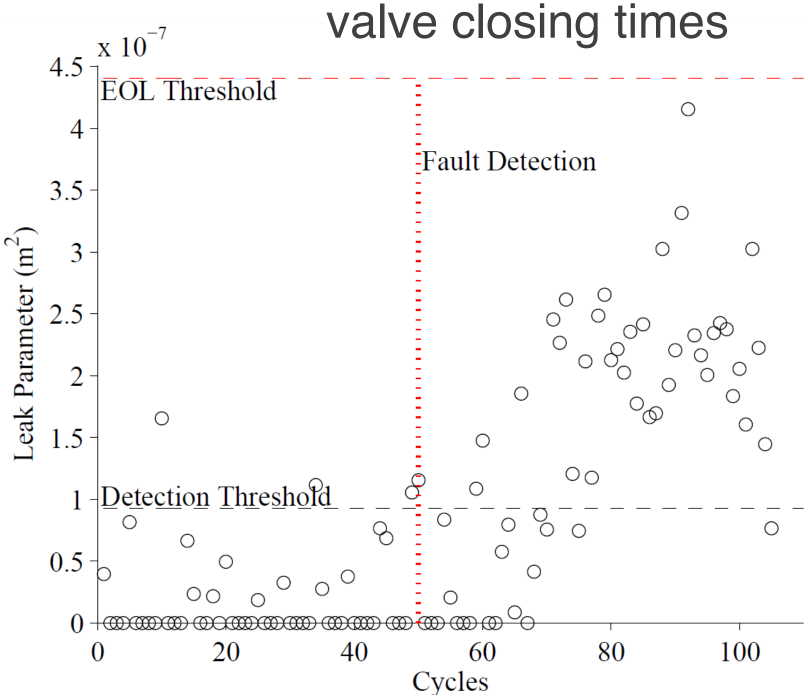




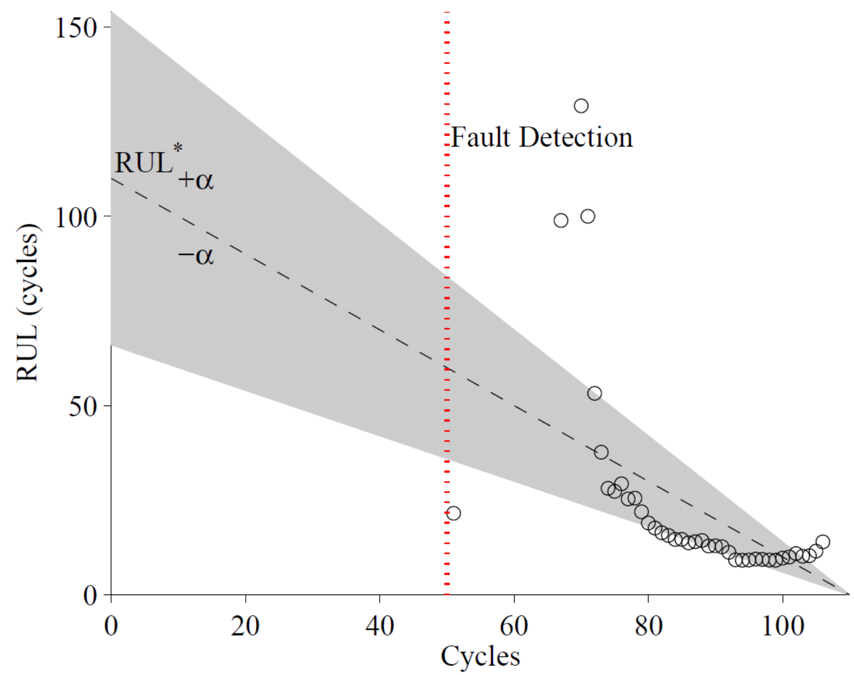
- Proportional valve V1 injecting the fault in line opened
- At each cycle fault injection percentage increased by 1%

Testbed: DV Leak to Atmosphere

Estimated leak parameter values based on valve closing times

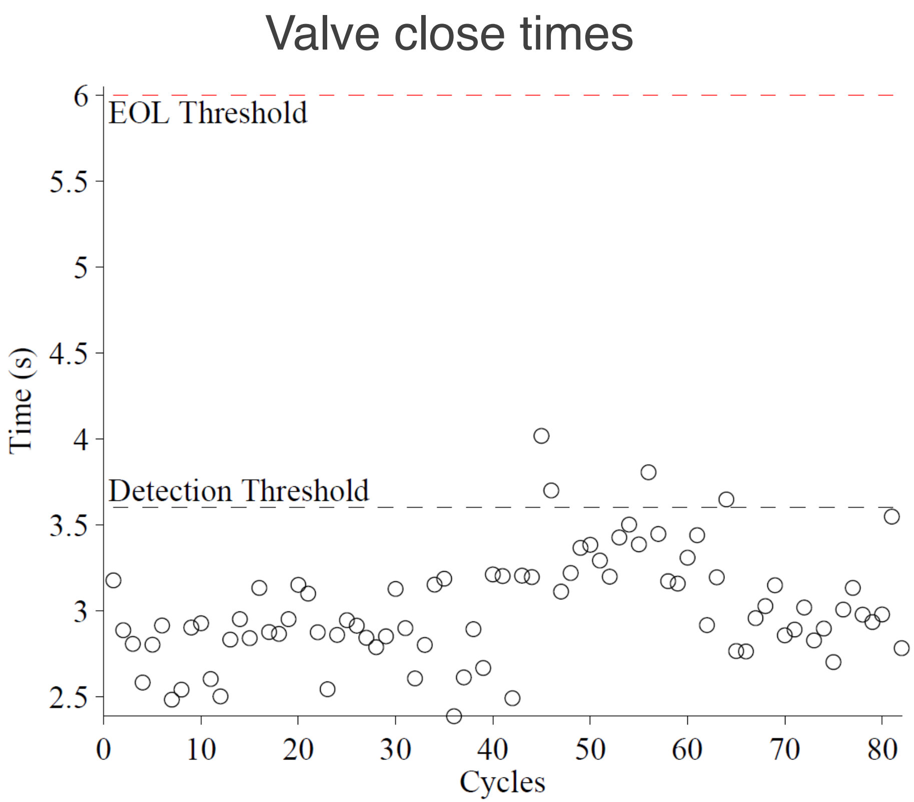


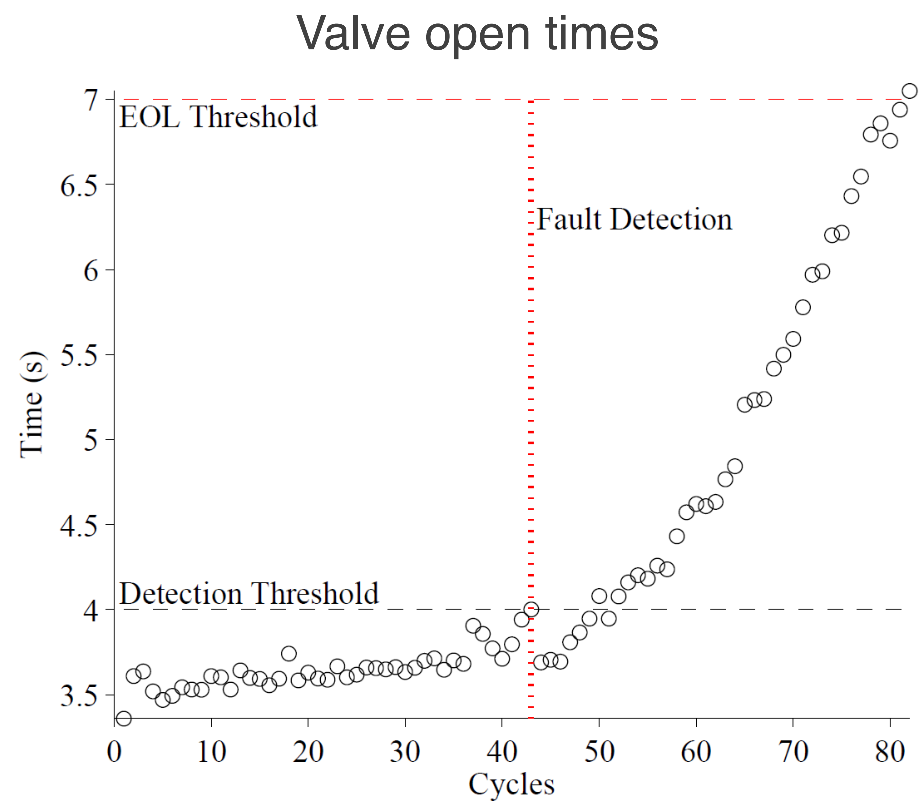
Predicted RUL values : α-λ plot



- 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

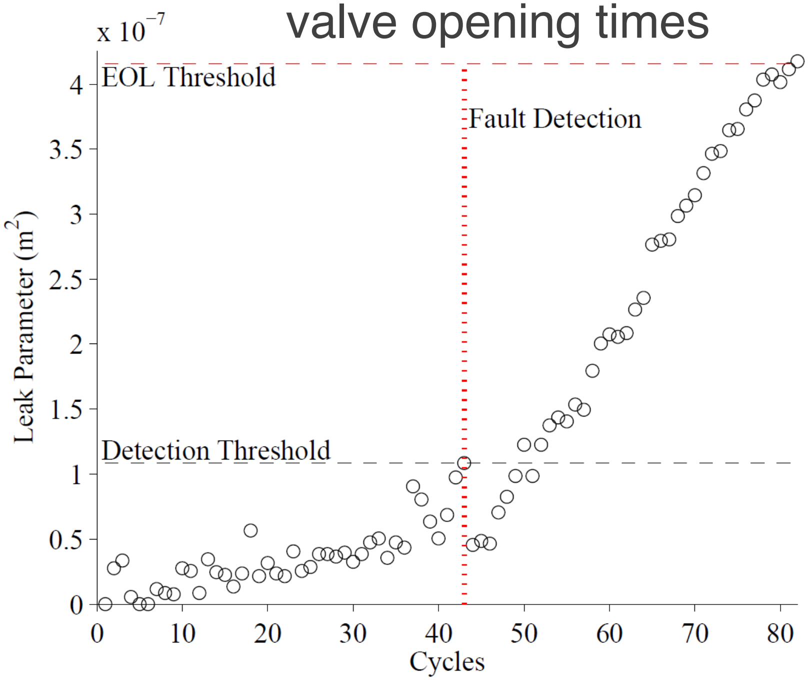




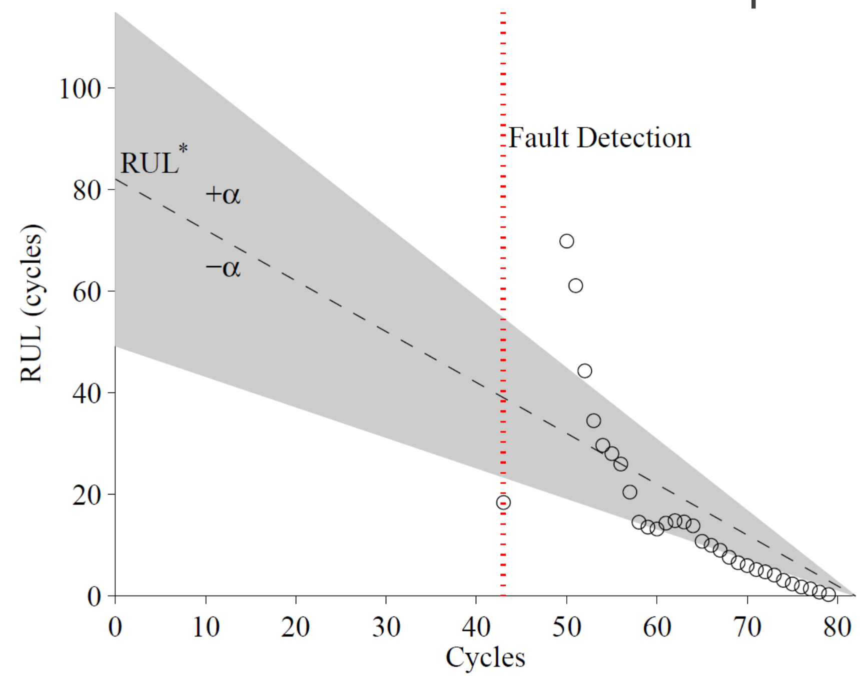
- Proportional valve V2 injecting the fault in line opened
- At each cycle fault injection percentage increased by 1%

Testbed: DV Leak from Supply

Estimated leak parameter values based on valve opening times



Predicted RUL values : α-λ plot



- Similar to atmosphere leak, fault is only observable at a certain magnitude
- Once observable, predictions being 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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