SCHOOL OF ENGINEERING
VANDERBILT UNIVERSITY

INSTITUTE FOR SOFTWARE
INTEGRATED SYSTEMS

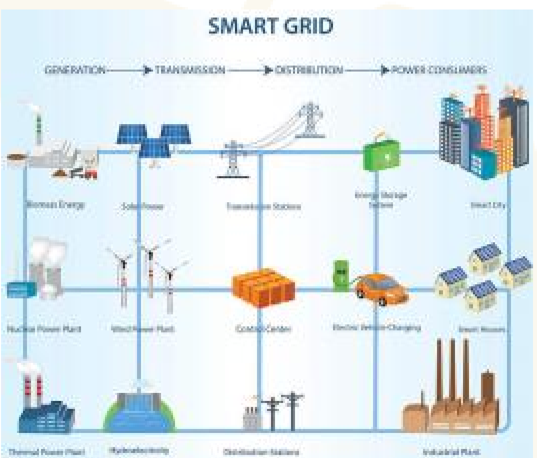
PANEL SESSION 11
THEORETICAL ASPECTS OF PROGNOSTICS

Gautam Biswas
Dept. of EECS/ISIS
Vanderbilt University

Motivation

- With the increasing complexity of today's safety-critical engineering systems, such as transportation, energy generation and distribution, and in manufacturing processes, guaranteeing
  - Safety of systems
  - Optimization of services (gain more with less)
  - Minimization of operational/maintenance costs (life cycle costs)

is becoming a very challenging



Motivation

- With increased autonomy demands, these issues are becoming even more central
- The interconnections between safety, optimization of services, minimization of maintenance costs provides both challenges and opportunities
  - How do we model and understand the behaviors of these system under different operating conditions?
  - Are there well-defined and closed form analytic formulations of system operations that are computationally feasible?
  - Can we develop algorithms that are robust to uncertainties and disturbances?
  - How do we validate these models and algorithms?
- Opportunity: Need to develop more systematic (theoretical) frameworks that link diagnostics, prognostics, control, and maintenance (Decision Making Problem)

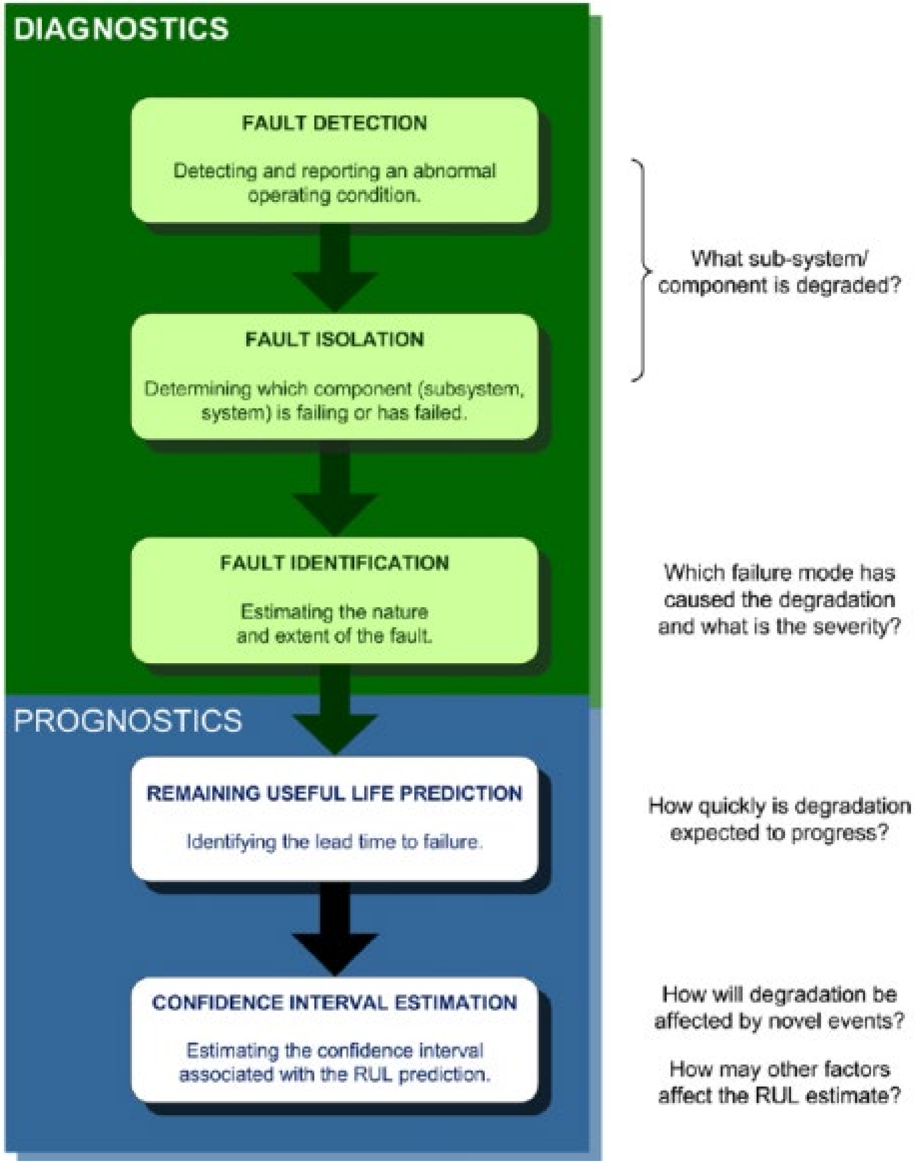
What is prognostics?

- ISO13381-1: "*an estimation of time to failure* (RUL, EOL) *and risk for one or more existing and future failure modes*"♣
  - Existing failure modes and deterioration rates,
  - Sensitivity of monitoring and analysis techniques to deterioration rates of failure modes
  - Interrelationship between failure modes and their deterioration rates,
  - Initiation criteria for future failure modes,
  - Effect of maintenance on failure degradations
  - Conditions and assumptions underlying the prognoses

♣ Sikorska, J. Z., Hodkiewicz, M., & Ma, L. (2011). Prognostic modelling options for remaining useful life estimation by industry. *Mechanical Systems and Signal Processing*, *25*(5), 1803-1836.

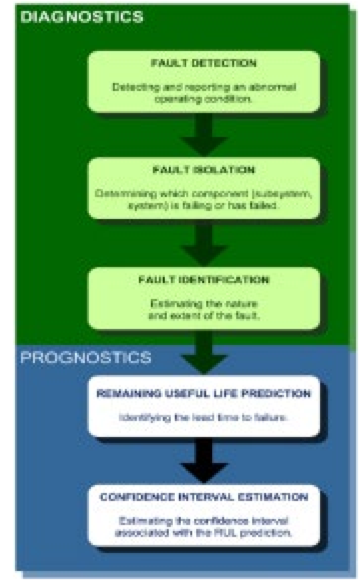
Traditional Prognostic modeling & analysis

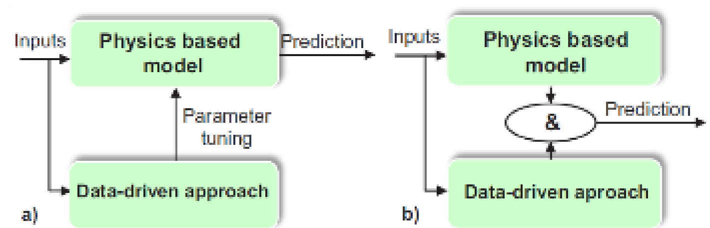
- Known failures and their degradation rates
- What influences these degradation rates?
  - Mode of operation
  - Environmental conditions
  - Operator actions and maintenance actions
- Strong relation between diagnostics and prognostics

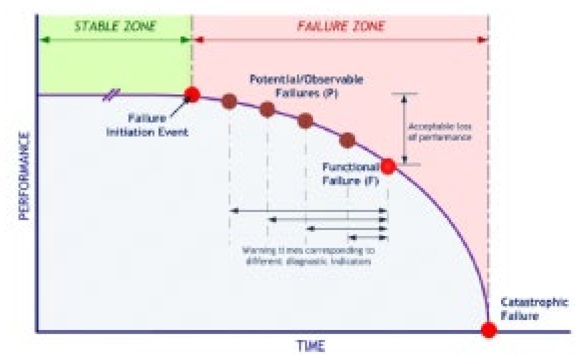


Traditional Approaches

- FDII algorithms (looking backwards)
  - Estimation task
  - Typically parameterized
  - Involves quantifying the values of deviated parameters
- Prognostics algorithms (looking forward)
  - Prediction task
  - Project forward: how components (represented by parameters) are going to degrade
    - Requires knowing future operating and environmental conditions
    - Model-driven (physics of failure); Data-driven (Regression; Bayesian, Neural network); Hybrid (model- + data-driven)♣
    - Methods are necessarily stochastic – predicted value + confidence bounds







♣Javed, K., Gouriveau, R., & Zerhouni, N. (2017). State of the art and taxonomy of prognostics approaches, trends of prognostics applications and open issues towards maturity at different technology readiness levels. *Mechanical Systems and Signal Processing*, *94*, 214-236.

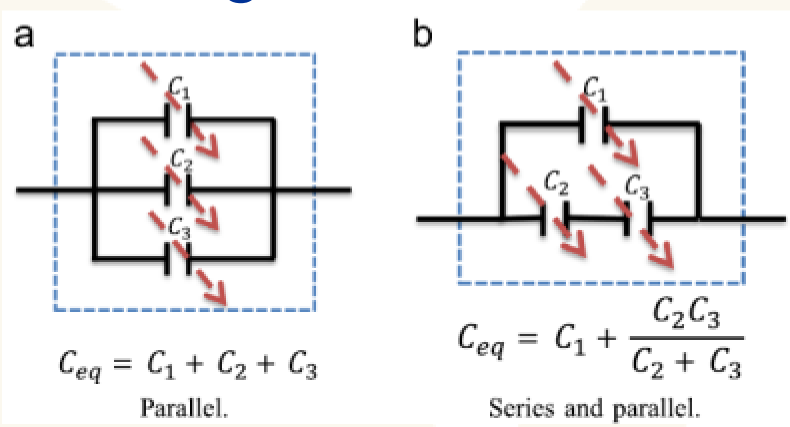
What are the limitations of traditional models?

- Typically deal with single components and their degradation modes?
  - Batteries, capacitors, switching elements, bearings, etc.
  - Supports Condition-based maintenance (CBM) & Decision Making for reliability/safety considerations?

- Question: Is this sufficient?
  - What is the effect of multiple degrading components on system behavior and performance? (System-level prognostics)
  - Interactions between failure modes & their deterioration rates (Future Failure mode prognostics)
    - Interactions – high vibration due to bearing degradation accelerates mechanical seal degradation
    - Cascades – one component exceeds specification limits; causes degradation in components down the line

Component → System-level effects

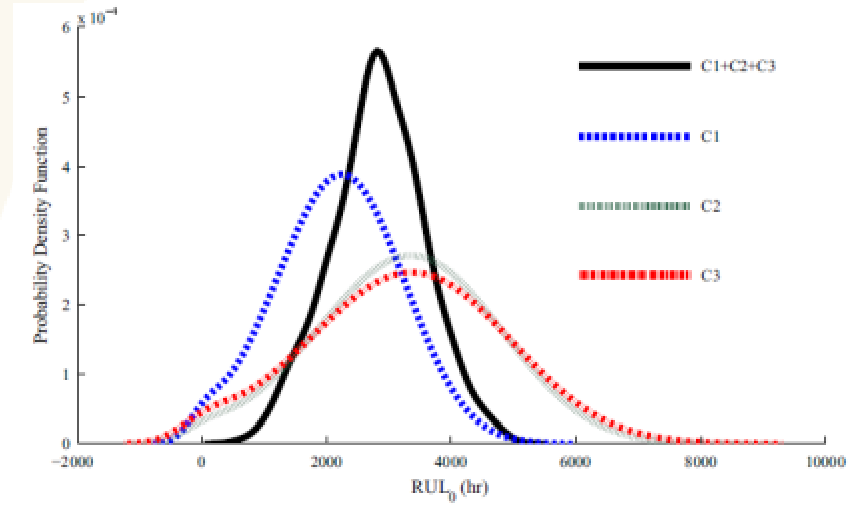
- Simple Example♣
- Two 3-capacitor configurations

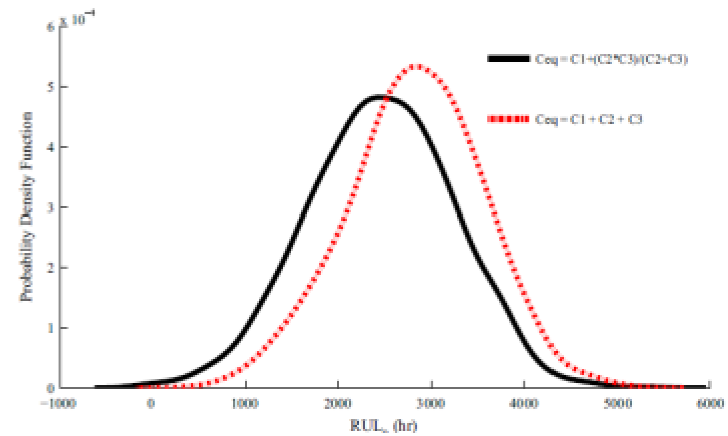


- Similar capacitors

Degradation model:

$$C_i(t + \Delta t) = (1 - \alpha_i) C_i(t)$$



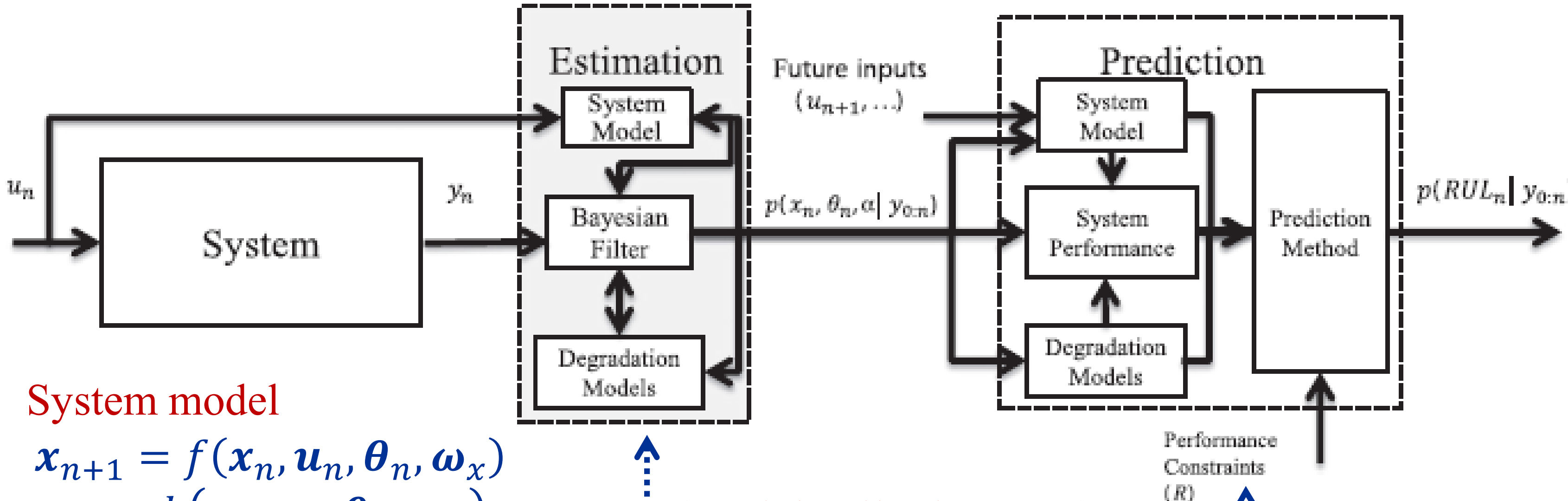


Comparison of configuration RUL's at $t = 0$

♣ Khorasgani, H., Biswas, G., & Sankararaman, S. (2016). Methodologies for system-level remaining useful life prediction. *Reliability Engineering & System Safety*, *154*, 8-18.

System Level RUL prediction

- Khorasgani, Biswas, & Sankararaman (2016)



System model

$$\boldsymbol{x}_{n+1} = f(\boldsymbol{x}_n, \boldsymbol{u}_n, \boldsymbol{\theta}_n, \boldsymbol{\omega}_x)$$
$$\boldsymbol{y}_n = h(\boldsymbol{x}_n, \boldsymbol{u}_n, \boldsymbol{\theta}_n, \boldsymbol{\omega}_y)$$

(Particle Filtering, SIR)

System degradation models; $D_i, i = 1,2,..,l$

$$\left.\begin{aligned} \boldsymbol{x}_{n+1} &= f(\boldsymbol{x}_n, \boldsymbol{u}_n, \boldsymbol{\theta}_n, \boldsymbol{\omega}_x) \\ \boldsymbol{\theta}_{n+1} &= g(\boldsymbol{\theta}_n, \alpha_n, \boldsymbol{x}_n, \boldsymbol{\omega}_D) \\ \boldsymbol{y}_n &= h(\boldsymbol{x}_n, \boldsymbol{u}_n, \boldsymbol{\theta}_n, \boldsymbol{\omega}_y) \end{aligned}\right]$$

$$EOL_n = \inf\{k \in Z; k \geq n \,\&\, T(p_k) = 1$$
$$RUL_n = (EOL_n - n)\Delta t$$

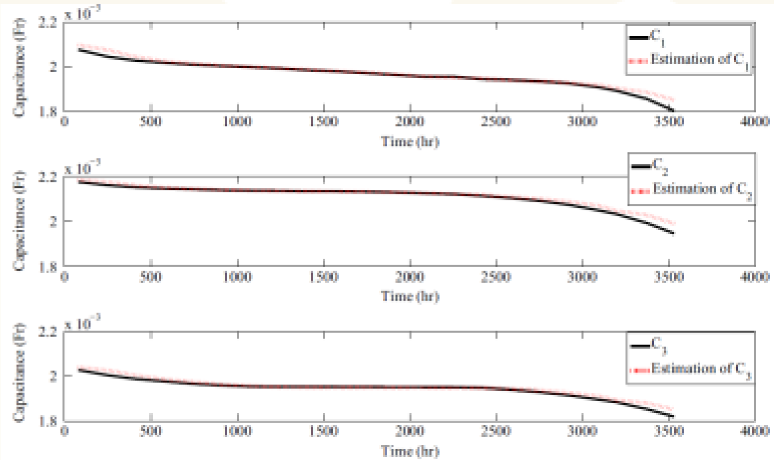
$$p_n = P_s(x_n, \theta_n)$$

System performance; p_n, given condtraints, $\mathrm{R} = \{r_i\}_{i=1,..,m}$

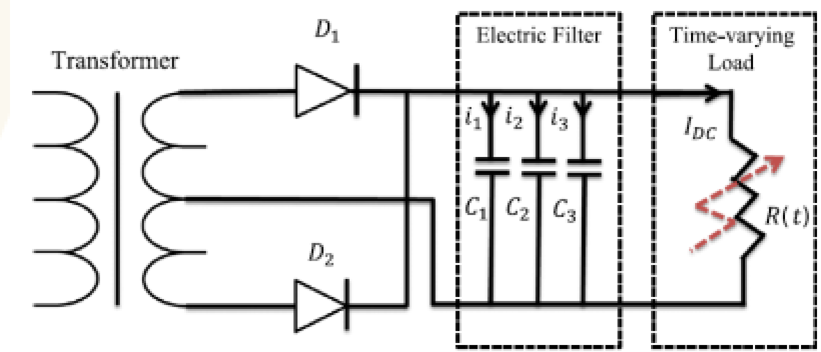
$$\boldsymbol{T}(\boldsymbol{p}_n) = \begin{cases} 1 \; if \; 0 \in R(p_n) \\ 0 \; if \; 0 \notin R(p_n) \end{cases}$$

System Level RUL

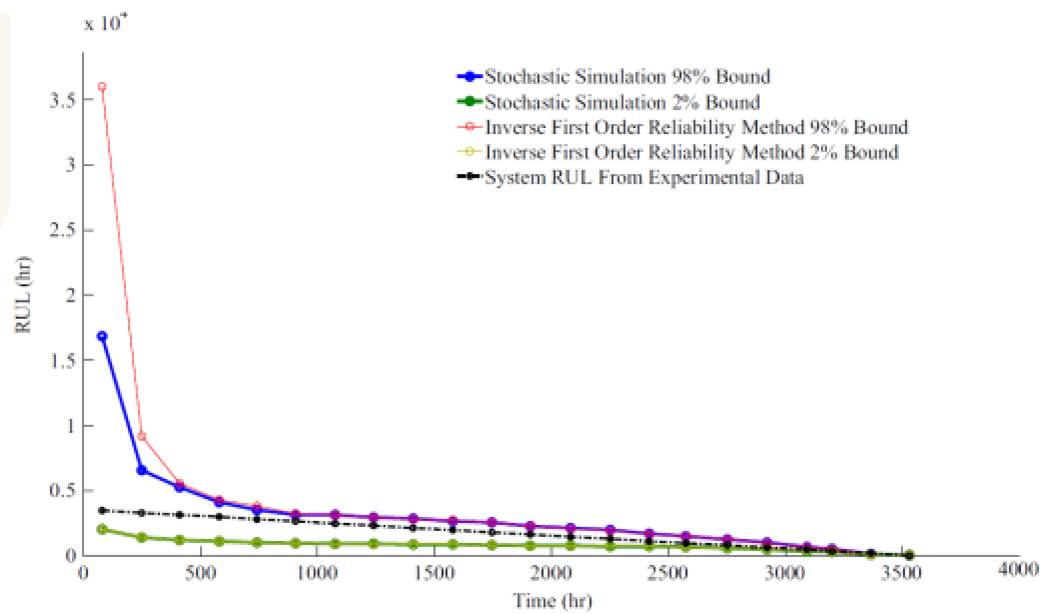
- Case Study



Capacitor degradation models



Full wave rectifier



98% bounds on RUL (CoV=0.1)

Evaluation metrics

- Performance of methods
  - Algorithm performance
    - Offline: accuracy, precision, horizon, bounds,
    - Online: precision index; convergence – steadiness index
  - Computational Performance (offline, online)
  - Cost-benefit risk – accuracy of RUL estimate (general); convergence (online methods)
- Applicability criteria (model vs data vs hybrid)
  - Is degradation process model required?
  - Generality and scope
  - How much (online) learning?
  - Assumptions & operating conditions
  - Modeling complexity & computation time

So where is the theory of prognostics?

- Still not widely applicable
  - Component-level prognosis used for CBM
  - System level prognostics in its infancy – used for broader decision making – offline and online components
  - Future failure mode prognosis – still a research problem – will need data driven methods to address; anomaly detection methods are promising; will they generalize?
  - Post Action prognosis -- identifying potential actions that could slow down or temporarily elimate progression of degradation to critical failure

Risk-based Decision Making Complexity

Need for accurate estimates, confidence bounds