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Office Of Nuclear Energy Sensors and Instrumentation Annual Review Meeting

Robust Online Monitoring Technology for Recalibration Assessment of Transmitters and Instrumentation

Pradeep Ramuhalli, Jamie Coble*
Pacific Northwest National Laboratory
*University of Tennessee

September 16-18, 2014

Project Overview

- **Goal: Develop and evaluate a standardized framework for next-generation online monitoring applicable to current and future nuclear systems**

- **Participants:**
  - PNNL (Pradeep Ramuhalli, Susan Crawford)
  - University of Tennessee (Jamie Coble)
  - AMS (Brent Shumaker)

- **Research directly supports primary goals of**
  - LWRS, ART, NGNP, MPACT

- **Supports secondary goals of**
  - AF and UNFD

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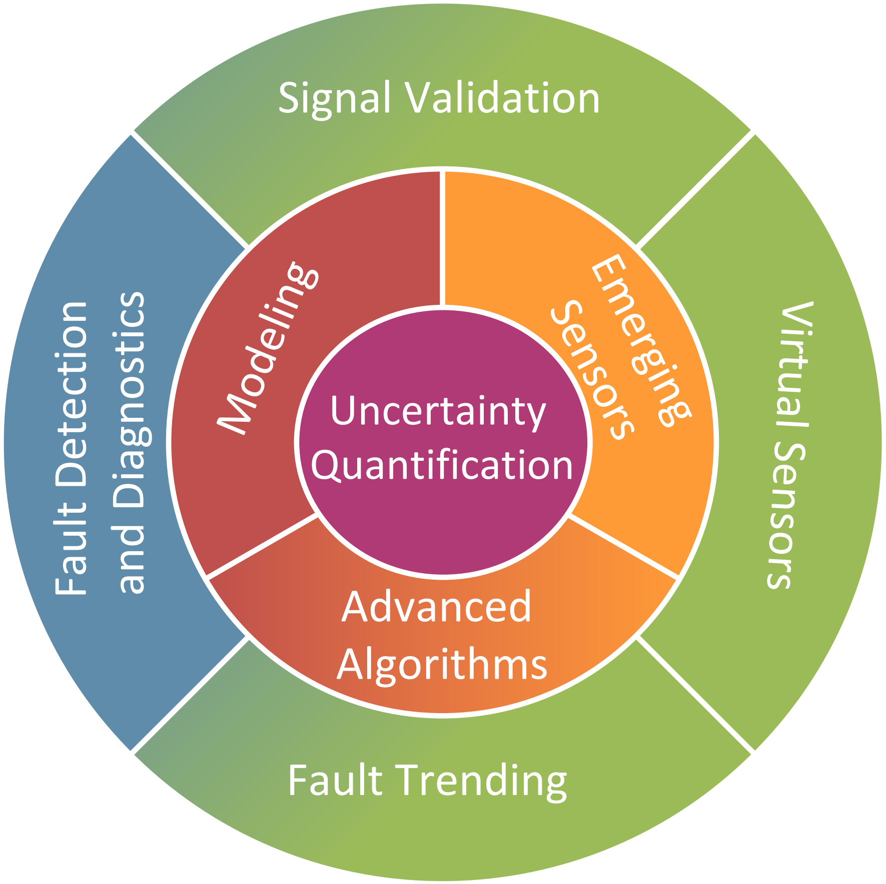
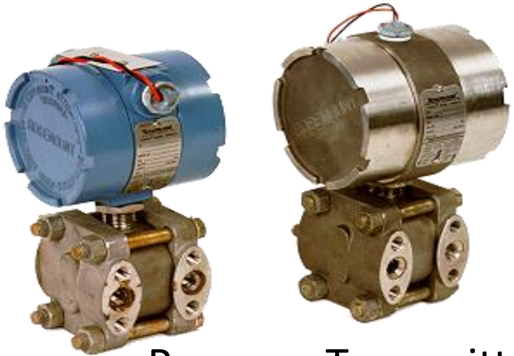
Objectives

- **Develop next-generation online monitoring applicable to current and future nuclear systems**
  - Apply data-driven UQ to develop methods for real-time calibration assessment and signal validation
  - Robust virtual sensors to augment available plant information
  - Technologies for sensor response-time characterization
  - Considerations for emerging I&C technologies

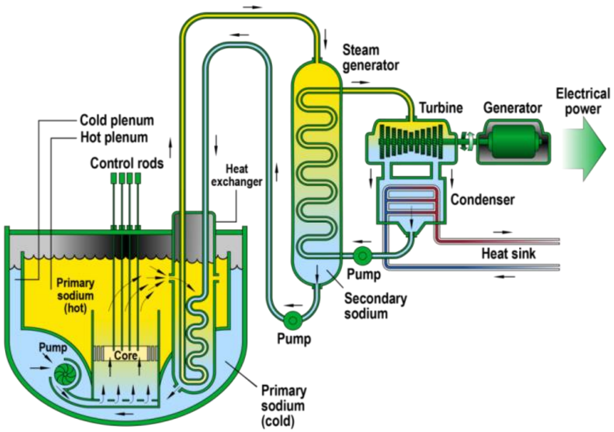


Project Background

- **Measurement reliability key to safe, economic and secure operation of nuclear systems**
  - Interval-based recalibration used to assure reliability
- **Current practices have several drawbacks**
  - Time consuming and expensive
  - Sensor calibration assessed infrequently
  - Contributes to ALARA
  - Unnecessary maintenance may damage healthy sensors
  - Potential for limited opportunities for maintenance in future nuclear systems
  - Different failure mechanisms for next-generation sensors and I&C



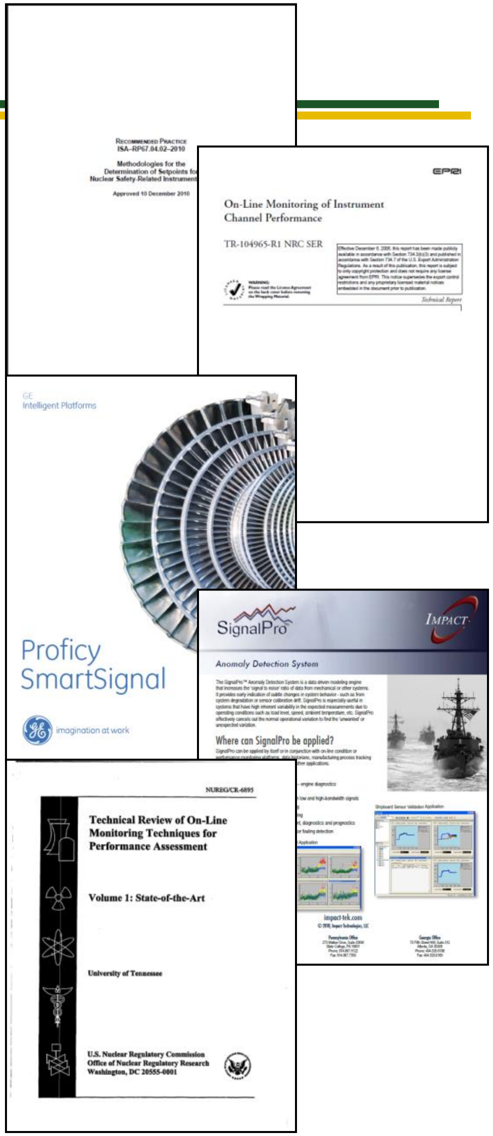
Pressure Transmitters



Sensor Performance Monitoring can Improve Reliability of Sensing

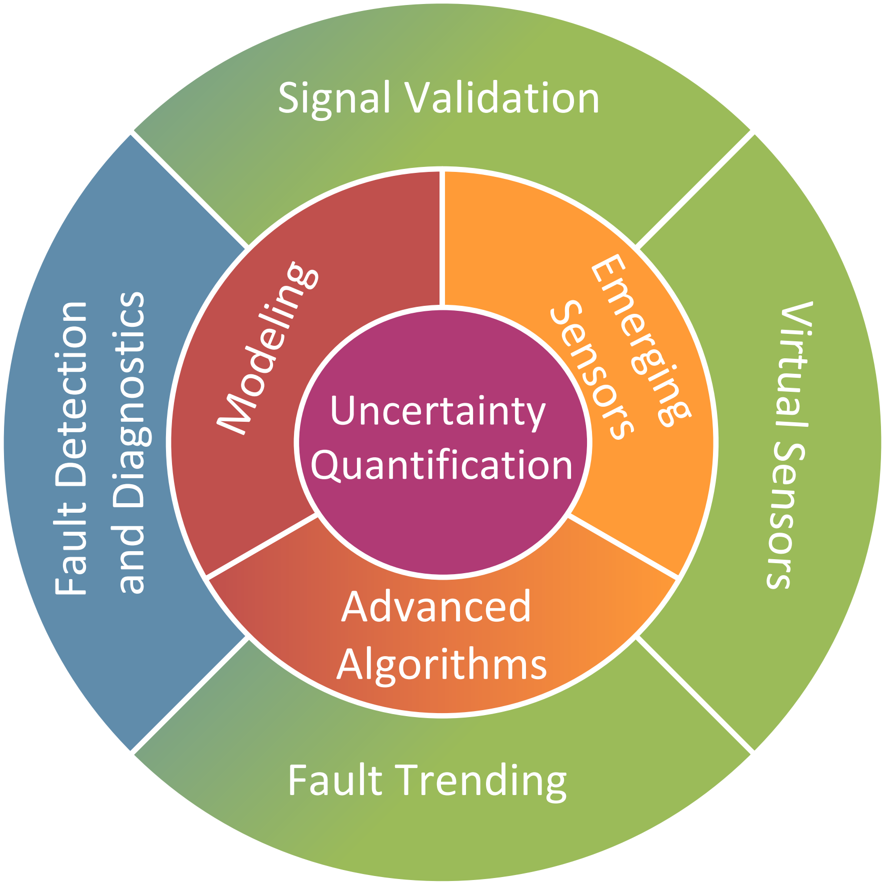
- **Online monitoring (OLM) supports condition-based calibration of key instrumentation**

- **OLM technologies can**
  - Temporarily accommodate limited sensor failure
  - Provide indications for measurements that cannot be made (virtual sensors)
  - Ensure reliability of next-generation sensors and instrumentation through formal methods for uncertainty quantification
  - Support extended sensor calibration cycles and reduce or eliminate TS-required periodic recalibration



Technology Impact

- **Standardized framework for next generation OLM that enables**
  - Recalibration needs assessment for dynamic and steady-state operation
  - Ability to derive plant information that currently cannot be measured
  - Predictive (over short-term) assessment of sensor failure
  - OLM framework for emerging I&C technologies
- **Applicability to current and future nuclear power systems**



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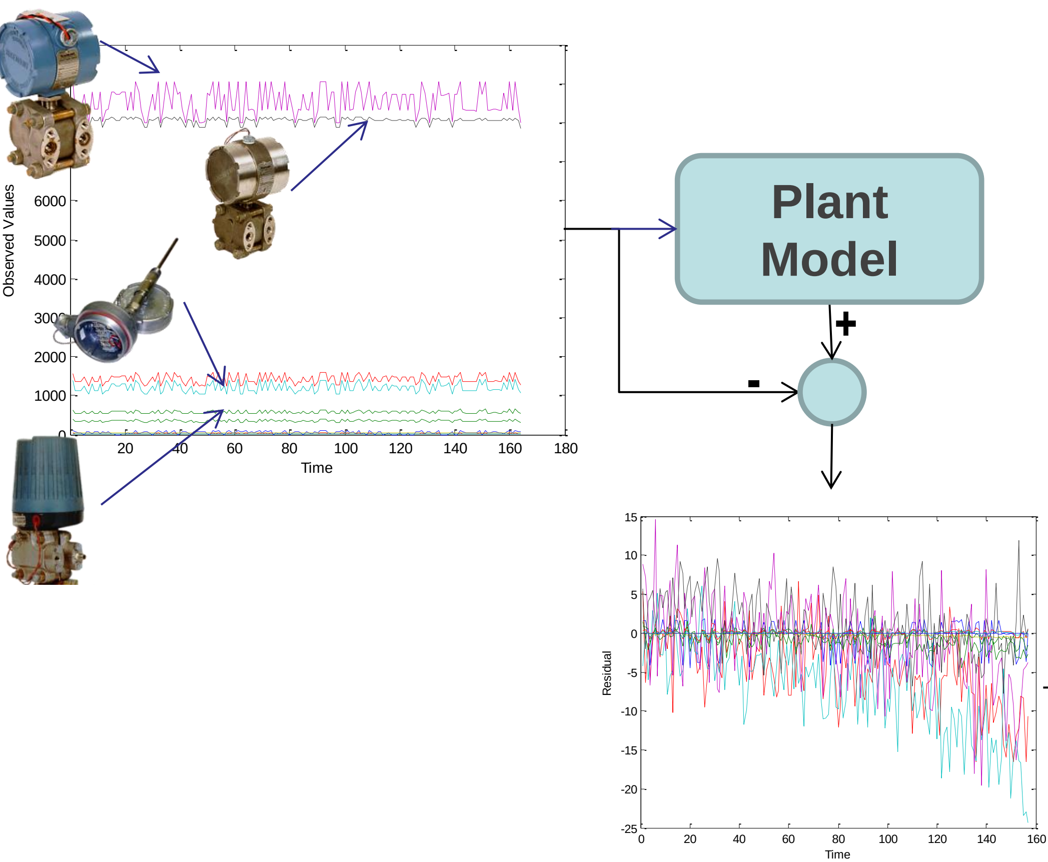
Research Plan (FY2015-FY2017)

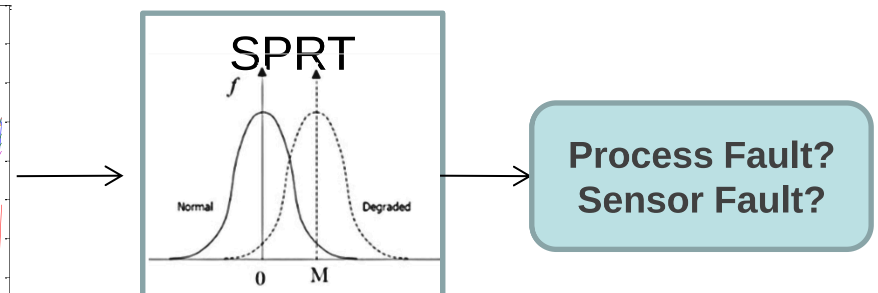
- **Signal validation and virtual sensors**
  - Evaluate how uncertainty drives minimum detection limits and acceptance criteria
  - Estimate expected measurement values (and associated uncertainties) for replacing faulted sensors
  - Evaluate the effect of using virtual sensors on OLM and OLM uncertainty
  - Develop guidelines for condition-based sensor recalibration
- **Assess impacts of next generation sensors and instrumentation**
  - Requirements definition for OLM in next generation I&C
  - Gaps assessment: Map algorithms (from other tasks) to requirements
- **Response time OLM**
  - Acceptance criteria development
  - Adapt research in signal validation for response time OLM
- **Verification and validation in a suitable test-bed or operating plant**

- **Budget**
  - Planned $1M over three years (FY2015-FY2017)

Technical Approach: Online Monitoring Overview



- **Non-intrusive**
  - Plant data collected during operation
- **Anomalies due to sensor fault vs. process change**
- **Acceptance criteria define normal performance bounds**

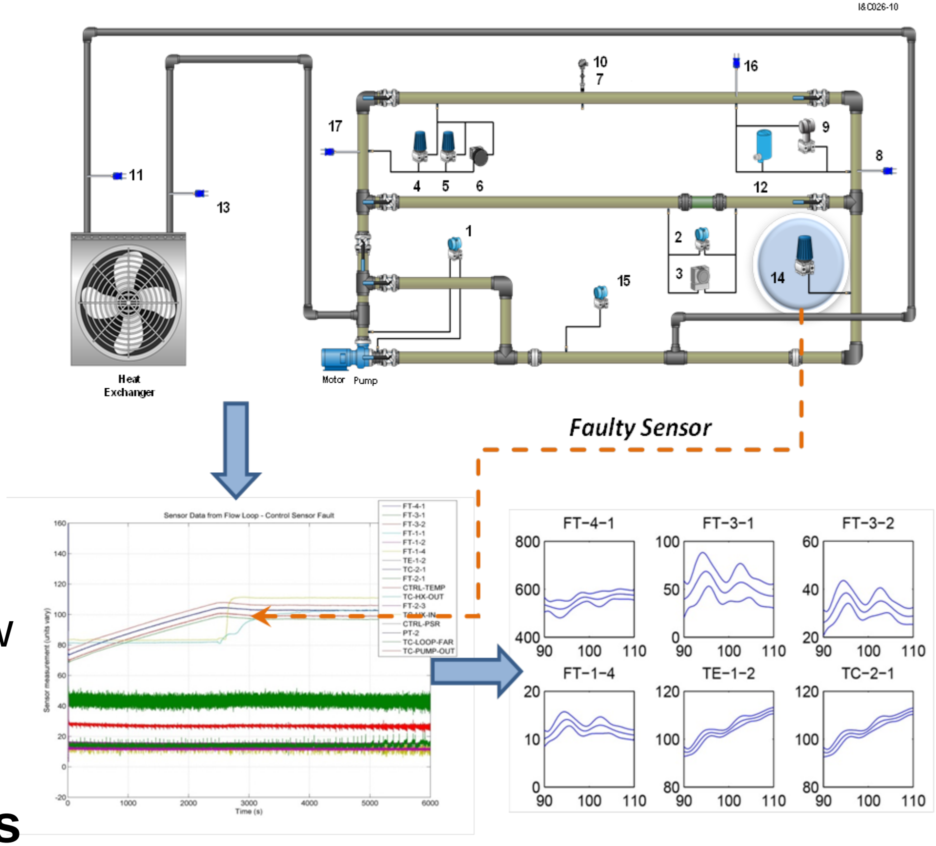


Accurate Uncertainty Quantification is Important to Online Monitoring

- **Uncertainty is inherent in any measurement process**
  - Process noise, sensor bias, electronic and measurement noise, etc.
- **OLM introduces new uncertainties**
  - Modeling uncertainty and bias
- **Current approach to evaluating measurement uncertainty may be overly conservative**
  - Uses manufacturer estimates of sensor noise
  - Conservative assumptions about sensor performance over the operating period
- **OLM uncertainty not independent of measurement uncertainty**
  - Both need to be considered together

Prior Work: Uncertainty Quantification (UQ)

- **Use Bayesian statistics to quantify uncertainty**
  - Combine what we already know (Prior) and the model discrepancy with the data (Likelihood).
- **Model represents relation between inputs (independent variables) and outputs (sensor outputs)**
  - Update the model in the light of new observations
- **Likelihood information using multi-output Gaussian processes that explicitly treat correlations between distinct output variables as well as space and/or time.**



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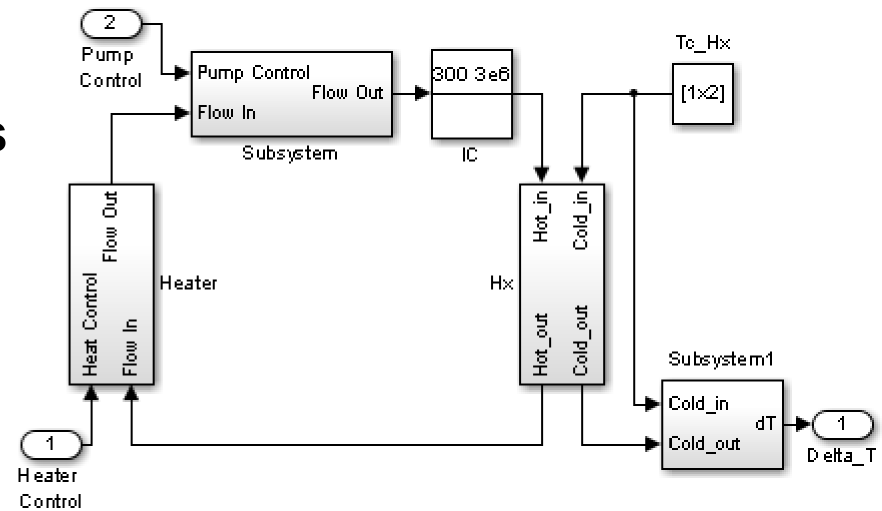
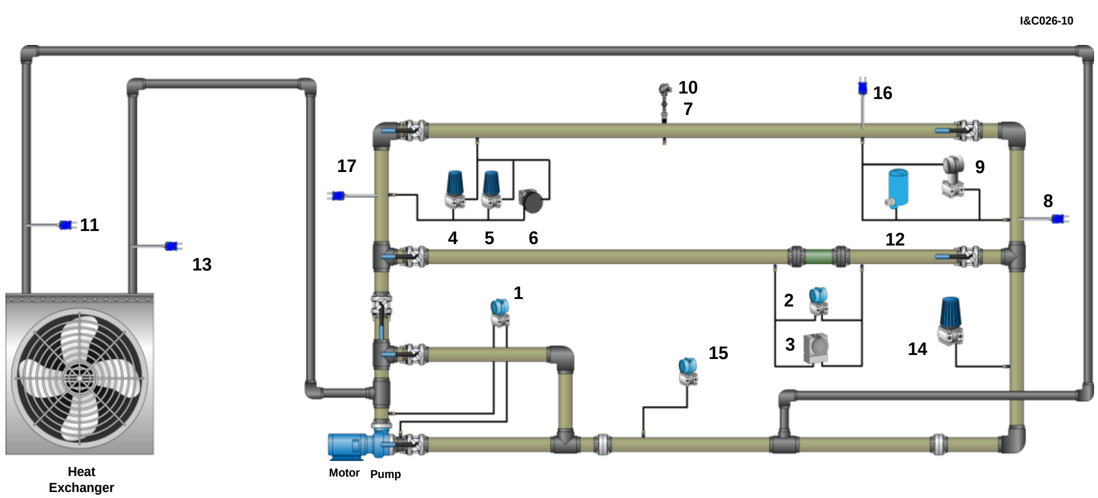
Data from Simulations and Testbeds to Evaluate UQ Methodology

- **Simple heat exchanger loop**
- **Sensor and instrumentation models coupled to loop model**
- **Prescribed uncertainty levels to directly study effects on sensed values and OLM results**
  - Normal and anomalous conditions





ITEM	ID	SENSOR TYPE	MANUFACTURER
1	FT-4-1	DIFFERENTIAL PRESSURE	ROSEMOUNT
2	FT-3-1	DIFFERENTIAL PRESSURE (SMART)	ROSEMOUNT
3	FT-3-2	DIFFERENTIAL PRESSURE	BARTON
4	FT-1-1	DIFFERENTIAL PRESSURE	FOXBORO
5	FT-1-2	DIFFERENTIAL PRESSURE	FOXBORO
6	FT-1-4	DIFFERENTIAL PRESSURE (SMART)	BARTON
7	TE-1-2	RTD (SMART)	ROSEMOUNT
8	TC-2-1	THERMOCOUPLE TYPE-J (SMART)	ROSEMOUNT
9	FT-2-1	DIFFERENTIAL PRESSURE	SCHLUMBERGER
10	CTRL-TEMP	RTD (SMART)	ROSEMOUNT
11	TC-HX-OUT	THERMOCOUPLE TYPE-J	OMEGA
12	FT-2-3	DIFFERENTIAL PRESSURE	HONEYWELL
13	TC-HX-IN	THERMOCOUPLE TYPE-J	OMEGA
14	CTRL-PSR	GAUGE PRESSURE	FOXBORO
15	PT-2	GAUGE PRESSURE	ROSEMOUNT
16	TC-LOOP-FAR	THERMOCOUPLE TYPE-E	OMEGA
17	TC-PUMP-OUT	THERMOCOUPLE TYPE-K	OMEGA

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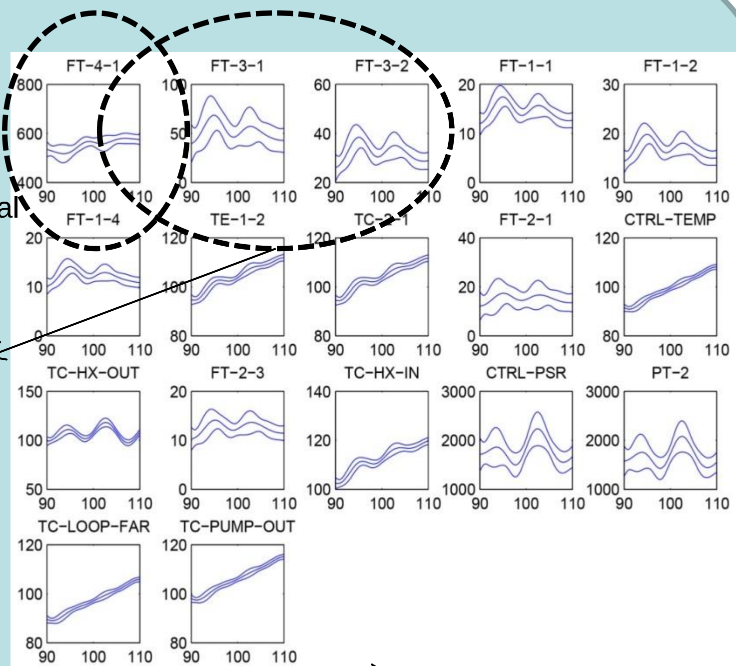
Results from UQ

Differential Pressure

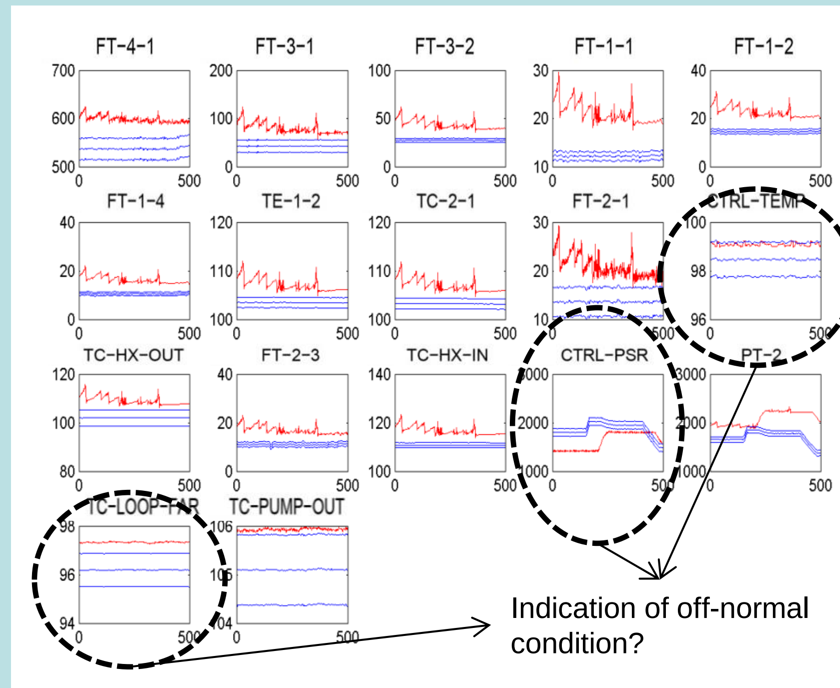
Redundant sensors



Control Temperature (ºF)

Data from Normal Operations

Snapshot in time (uncertainty bounds change with time)



Time (samples)

Data from Control Pressure Sensor Fault

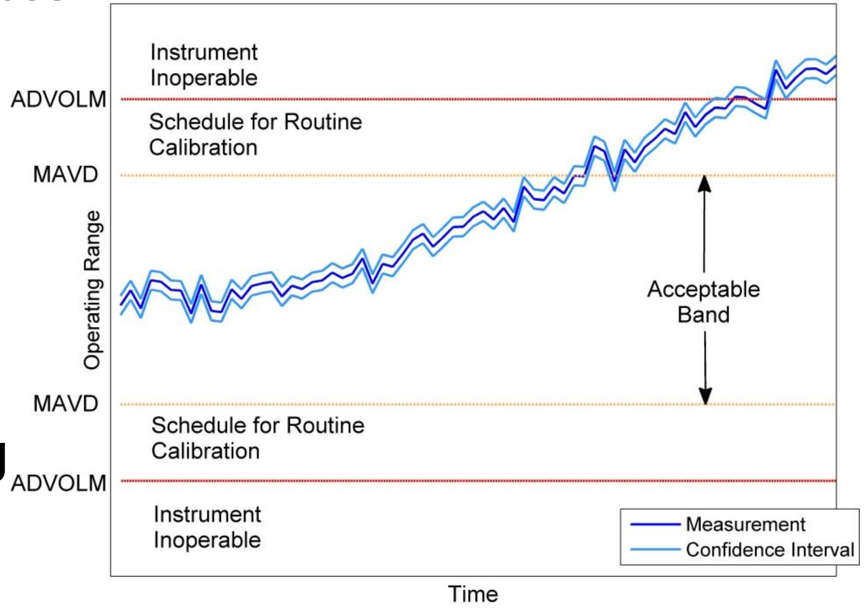
Snapshot over time window, using models in predictive mode

Accomplishments

- **Reviewed state of the art in OLM for sensor calibration assessment and identified technical gaps (PNNL-21687)**
- **Development of framework for data-driven uncertainty quantification (PNNL-22847.R1)**
- **Journal/Conference papers and presentations**
  - "Extending Sensor Calibration Intervals in Nuclear Power Plants," *Transactions of the ANS* 107:327-328, 2012.
  - "Recalibration methodology for transmitters and instrumentation," 2012 ANS NPIC/HMIT
  - "Calibration Monitoring for Sensor Calibration Interval Extension: Identifying Technical Gaps," 2012 Future of Instrumentation International Workshop
  - "Online Sensor Calibration Assessment in Nuclear Power Systems," *Invited paper*, *IEEE I&M Magazine* 16(3):32-37, 2013. doi: 10.1109/MIM.2013.6521132
  - "Advanced algorithms for online calibration monitoring of transmitters and instrumentation," Presented at *ANS Utility Working Conference* (August 2013)
  - "Approaches to quantify uncertainty in online sensor calibration monitoring," 2013 ANS Winter Meeting.

Path Forward: Signal Validation & Emerging I&C

- **Proposed OLM programs require periodic recalibration of a limited set of sensors**
- **Signal validation could potentially alleviate that requirement with high-confidence assessment of sensor status**
  - Accurate uncertainty quantification
  - Combining disparate information sources
- **Signal validation approaches can also be used as a preprocessing step before advanced monitoring and control algorithms to ensure decisions are based on quality data**
- **OLM requirements using emerging I&C technologies unknown**



Path Forward: Virtual Sensors

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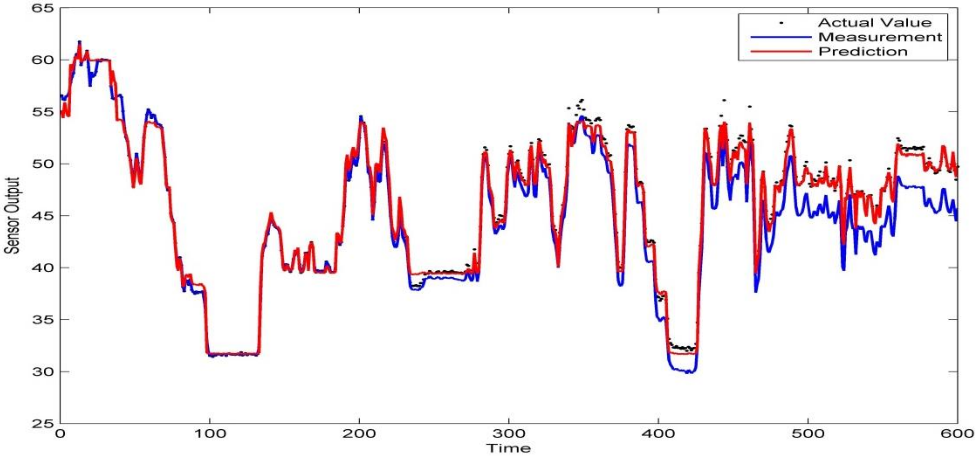
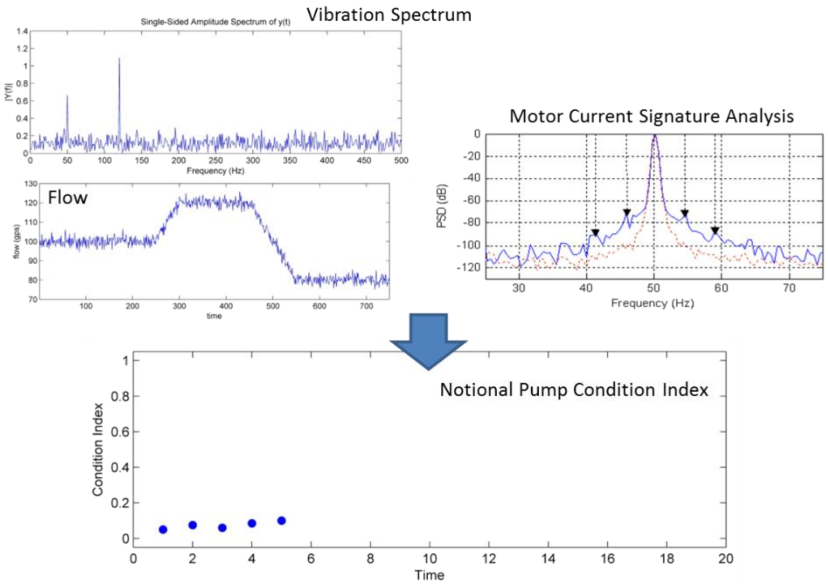
- OLM estimates can replace faulty sensor measurements
  - Uncertainty must account for spillover of faulty reading into estimate





- Measurements can be combined to provide additional signatures that aren't currently measureable

Conclusion

- **Research focused on addressing high-impact technical gaps to developing a standardized framework for robust next-generation online monitoring**
- **Outcomes enable**
  - Extended calibration intervals and relief of even limited periodic assessment requirements
  - Assessment of sensor measurement accuracy with high confidence
  - Derived values for desired parameters that cannot be directly measured
- **Outcomes support**
  - Improved reliability and economics for current and future nuclear systems
  - Deployment of advanced sensors (ultrasonic, fiber optic, etc.) and instrumentation (digital I&C, wireless, etc.)