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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

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Project Overview

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

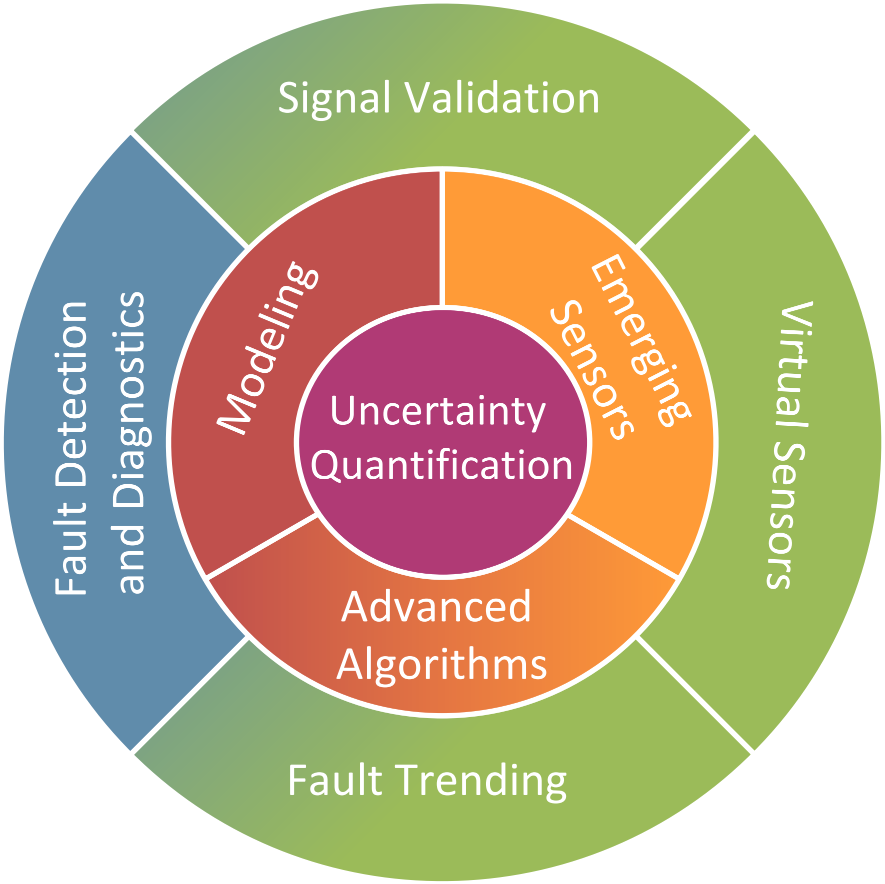
- **Participants:**
  - PNNL (Pradeep Ramuhalli, Susan Crawford)
  - University of Tennessee (Jamie Coble)
  - AMS (Brent Shumaker)

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

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

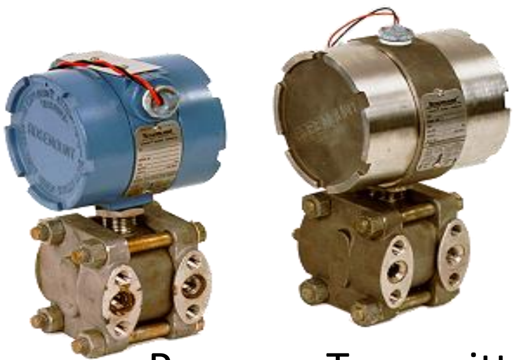
Objectives

- **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

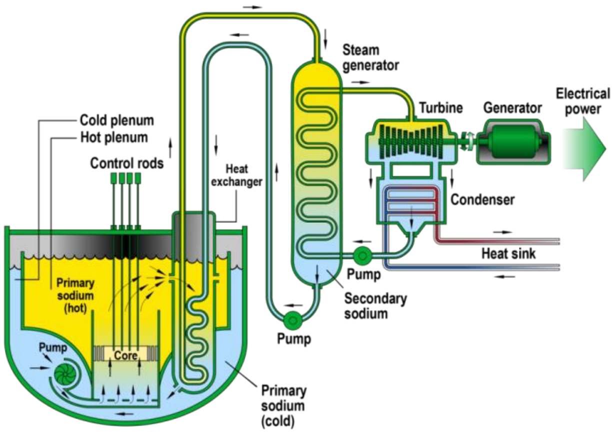


Project Background

- **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

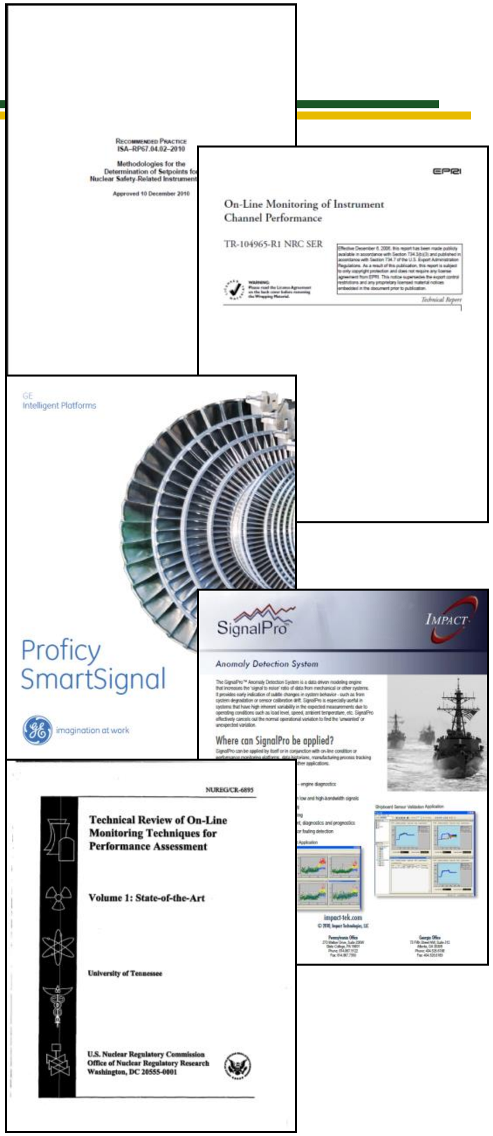


Pressure Transmitters



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



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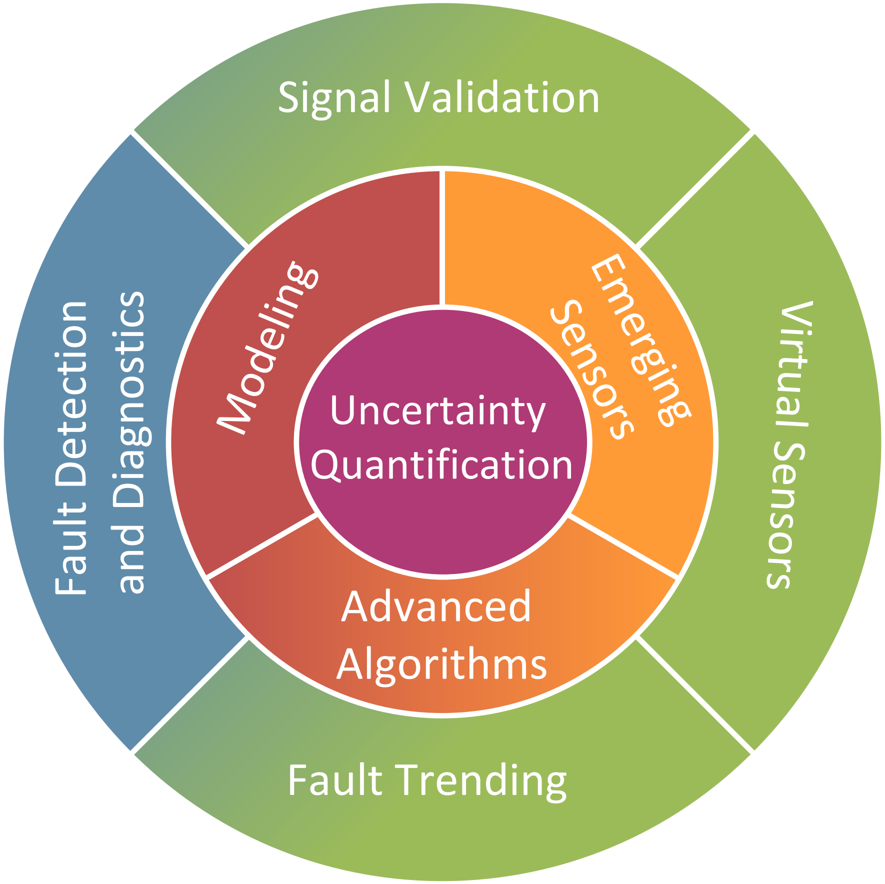
Technology Impact

- **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**



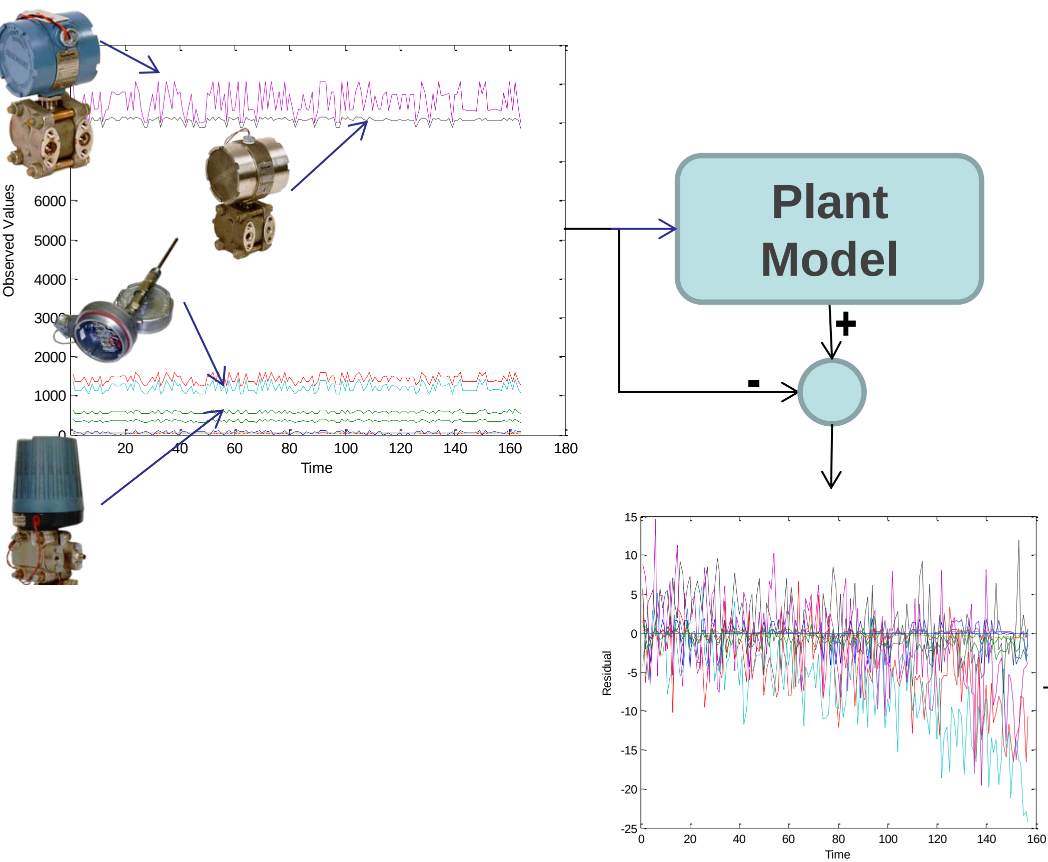
Research Plan (FY2015-FY2017)

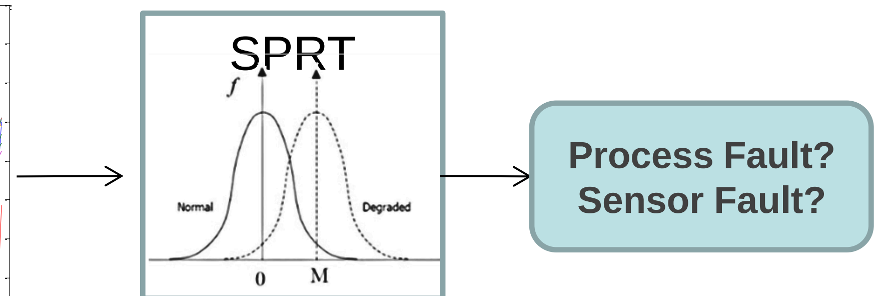
- **Signal validation and virtual sensors**
  - Evaluate how uncertainty drives minimum detection limits and acceptance criteria
  - Estimate expected measurement values (and associated uncertainties) for replacing faulted sensors
  - Evaluate the effect of using virtual sensors on OLM and OLM uncertainty
  - 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**



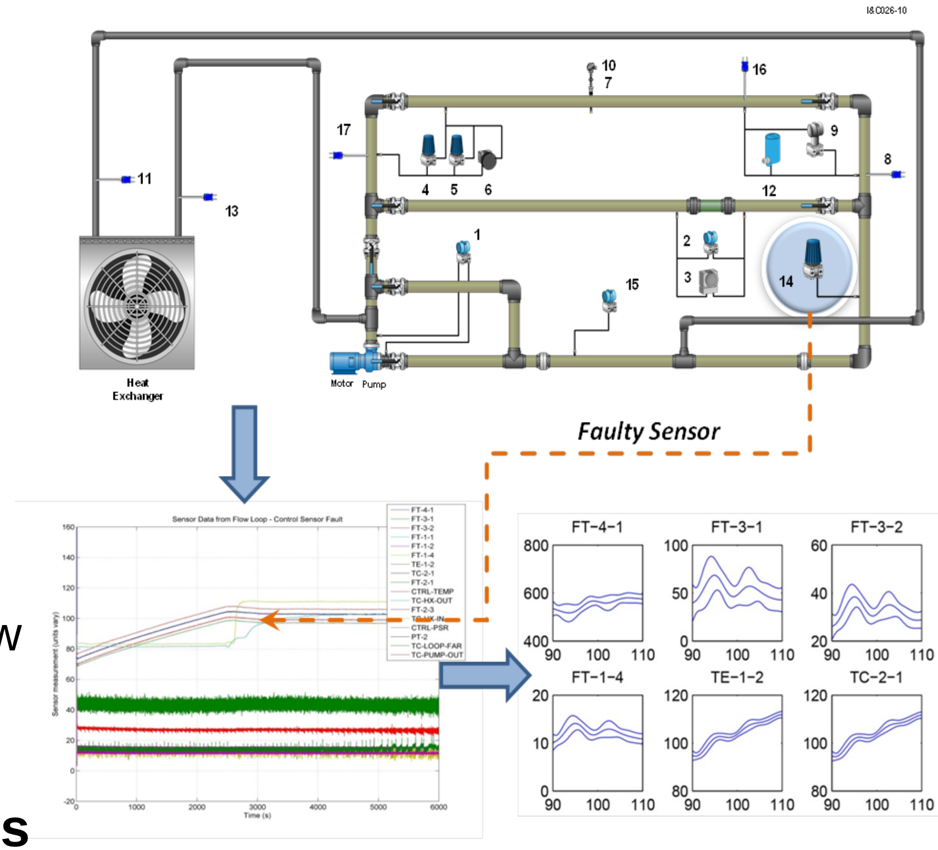


Accurate Uncertainty Quantification is Important to Online Monitoring

- **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

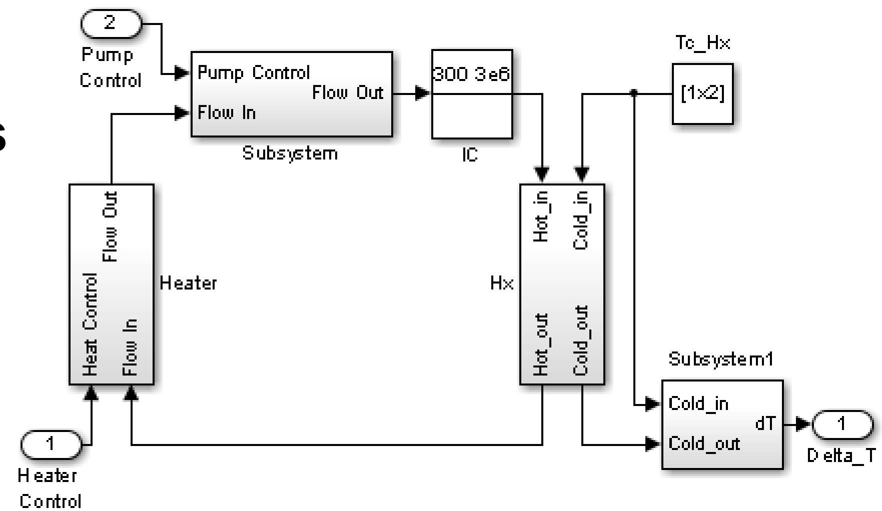
Prior Work: Uncertainty Quantification (UQ)

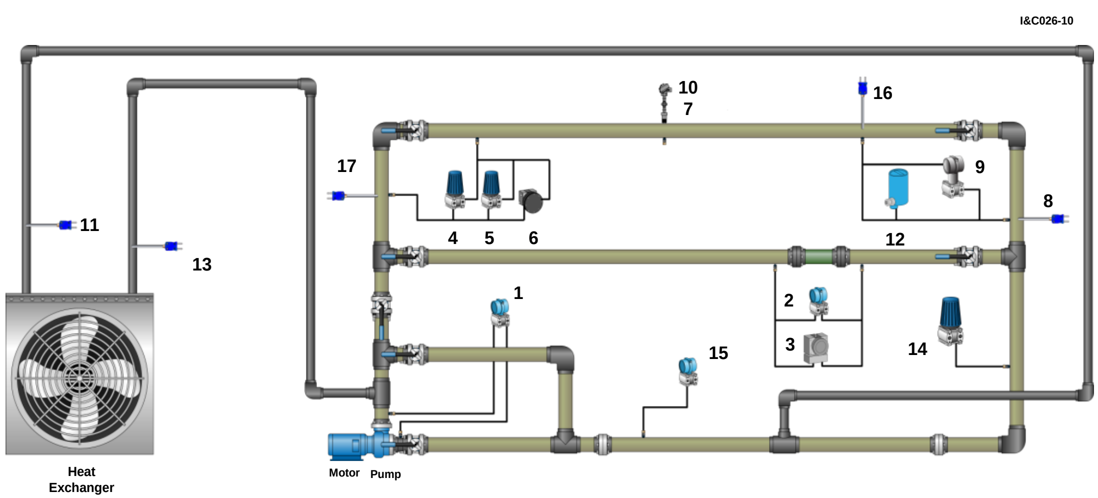
- **Use Bayesian statistics to quantify uncertainty**
  - Combine what we already know (Prior) and the model discrepancy with the data (Likelihood).
- **Model represents relation between inputs (independent variables) and outputs (sensor outputs)**
  - Update the model in the light of new observations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



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



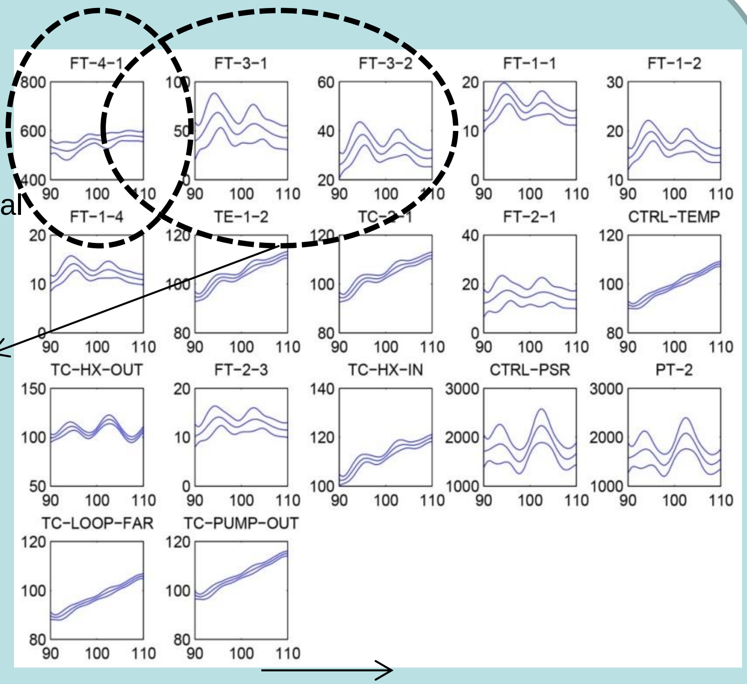


ITEM	ID	SENSOR TYPE	MANUFACTURER
1	FT-4-1	DIFFERENTIAL PRESSURE	ROSEMOUNT
2	FT-3-1	DIFFERENTIAL PRESSURE (SMART)	ROSEMOUNT
3	FT-3-2	DIFFERENTIAL PRESSURE	BARTON
4	FT-1-1	DIFFERENTIAL PRESSURE	FOXBORO
5	FT-1-2	DIFFERENTIAL PRESSURE	FOXBORO
6	FT-1-4	DIFFERENTIAL PRESSURE (SMART)	BARTON
7	TE-1-2	RTD (SMART)	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

Results from UQ

Differential Pressure

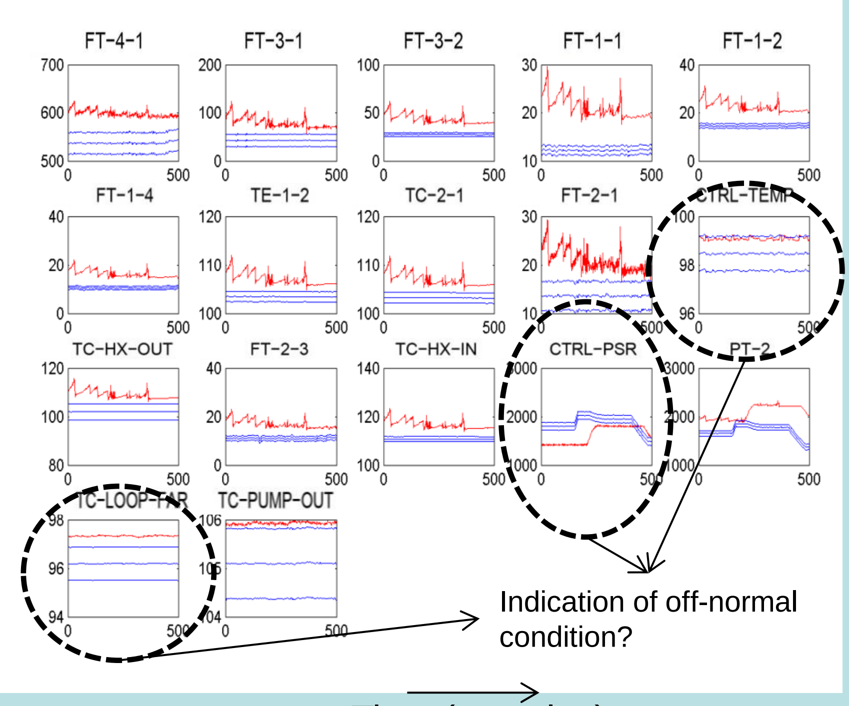
Redundant sensors



Control Temperature (ºF)

<u>*Data from Normal Operations*</u>

Snapshot in time (uncertainty bounds change with time)



Time (samples)

<u>*Data from Control Pressure Sensor Fault*</u>

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

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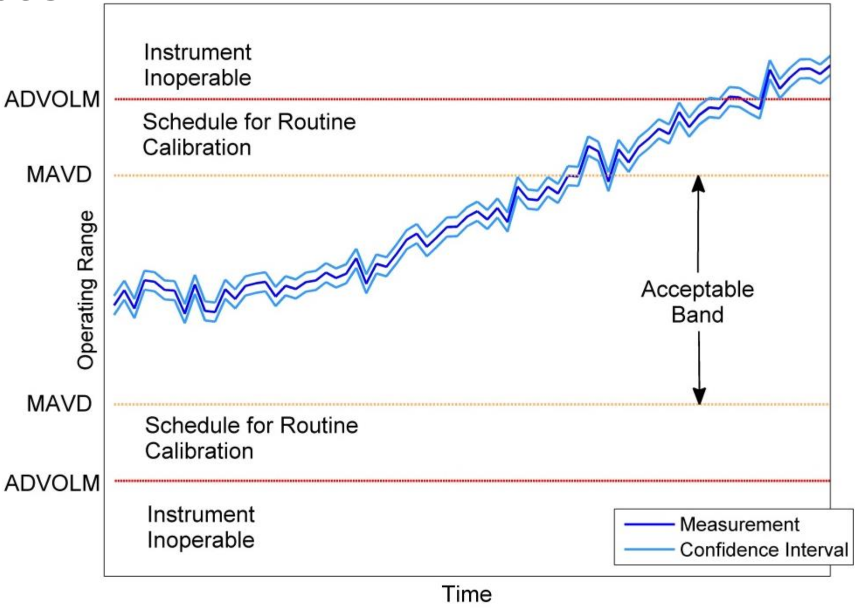
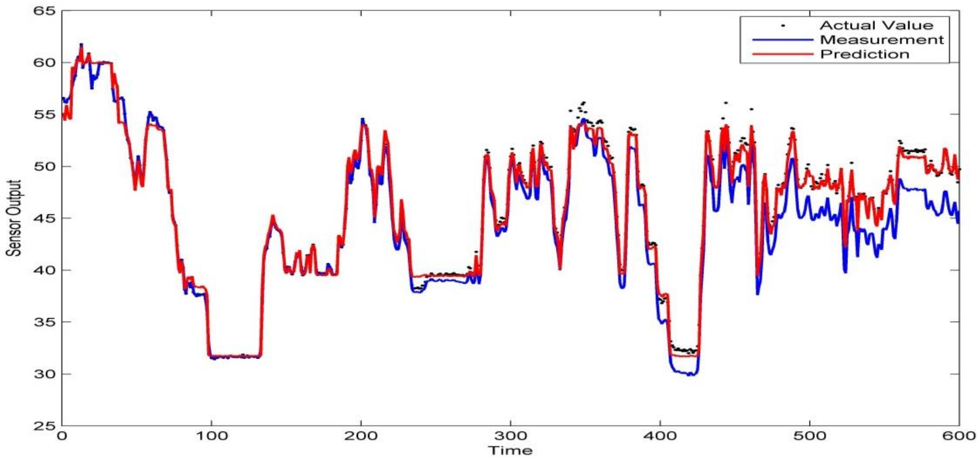
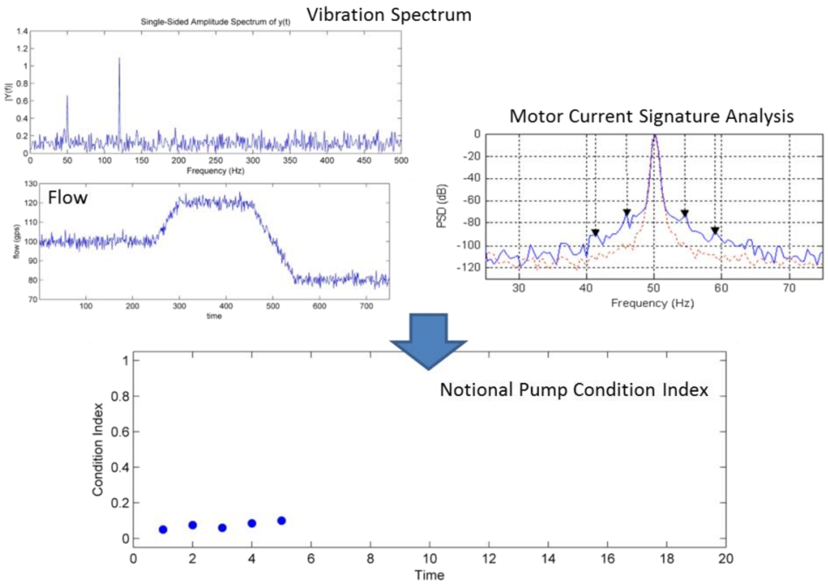
- **Proposed OLM programs require periodic recalibration of a limited set of sensors**
- **Signal validation could potentially alleviate that requirement with high-confidence assessment of sensor status**
  - Accurate uncertainty quantification
  - Combining disparate information sources
- **Signal validation 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

- 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.)