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

Participants:
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- AMS (Brent Shumaker)

Research directly supports primary goals of
- LWRS, SMR, ARC, NGNP, and MPACT

Supports secondary goals of
- AF and UNFD
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

Open questions
- Temporarily accommodate limited sensor failure
- Ensure reliability of next generation sensors and instrumentation
- Robust methods for uncertainty quantification (UQ)
Technology Impact

- **Standardized framework for next generation Online Monitoring (OLM) that supports**
  - Dynamic and steady-state operation
  - Real-time calibration assessment and signal validation
  - Considerations for emerging I&C technologies

- **Four-year project addresses cross-cutting areas**
  - Uncertainty quantification
  - Virtual sensors
  - OLM requirements for next-generation I&C
Research Plan

- OLM Requirements and Technical Gaps assessment (FY12)
- Quantifying uncertainty in OLM results (FY13)
  - Develop a model-neutral mathematical framework for estimating uncertainty in OLM under normal and anomalous plant operation conditions
- Establishing methods for virtual sensors and signal validation (FY14)
  - Evaluate how uncertainty drives minimum detection limits
  - 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 (FY15)
  - Evaluate effect of proposed next generation I&C systems on OLM
- Transition to demonstration in a suitable test-bed or operating plant (FY15/FY16)
- Budget

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<th>FY13</th>
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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**

![Diagram showing plant monitoring and residual analysis](image.png)
Technical Approach: Uncertainty Quantification

- Several possible approaches to UQ
  - Deterministic sampling approaches
  - Stochastic approaches
  - Generalized linear model, Multivariate adaptive regression splines model
  - Multi-output Gaussian process model, polynomial chaos model

- Evaluating approaches to determine appropriate UQ methodology
  - Bayesian model selection (Bayesian LASSO, Bayesian Elastic net, etc.)
  - Cross-validation approaches
  - Evaluation based on information criteria (Akaike information criteria (AIC), Bayesian information criteria (BIC), etc.)

- Validation of UQ methodology using simulated and experimental data
  - Bayesian model calibration
  - Cross-validation approaches
  - Validation based on Mean Squared Prediction Error (MSPE)
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
FY 12 Accomplishments

- Reviewed state of the art in OLM for sensor calibration assessment and identified technical gaps (PNNL-21687)
  - Standardized approach to uncertainty quantification
  - Method to establish acceptance criteria and evaluate the effects of acceptance criteria on plant setpoints
  - Method to provide virtual sensor estimates for unavailable measurements
  - Evaluation of the effects of digital I&C, wireless communication, and emerging sensor types on OLM

- Development of initial research plan to address gaps
  - Technical development to address gaps in FY13 – FY15
  - Demonstration in FY16

- Journal/Conference papers
  - “Extending Sensor Calibration Intervals in Nuclear Power Plants,” 2012 ANS Winter meeting
FY 13 Activities

Development of preliminary framework for uncertainty quantification
- Comparison to current practices

Evaluation of UQ framework with simulated and experimental data
- Nominal operation
- Anomalous operation (sensor faults and process faults)

Journal/Conference Papers
- Planned presentation at ANS Utility Working Conference (August 2013) (Title TBD)
Technical Approach: 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
Technical Approach: 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
Planned Accomplishments

**FY14**
- Virtual sensors: Robust algorithms for estimating derived values for parameters that cannot be directly measured
- Data integration methods for high-confidence signal validation

**FY15**
- Integrate UQ methods with virtual sensors and signal validation approaches
- Methods to quantify effects of new sensing approaches and digital I&C on OLM

**FY16**
- Demonstration in a lab-scale system or secondary system at an NPP partner site
Crosscutting Benefits

- Project team interacting with cognizant experts from various DOE-NE programs to ensure broad-based input (e.g., LWRS, SMR, ARC, AF, MPACT)
- Interacting with industry experts to leverage current practices in OLM and UQ
- Defined list of requirements through survey of published literature and industry practices
  - Uncertainty quantification
  - High-confidence signal validation
  - Virtual sensor estimation
- Continued interactions
  - Continue to engage experts in various DOE-NE programs
  - Participate in program reviews to gain input and concurrence from cognizant experts
Crosscutting Benefits: LWRS, SMR, ARC, and NGNP

- **Unobtrusive assessment of sensor calibration**
  - Relaxation of interval-based recalibration requirements in favor of condition-based recalibration – reduced or eliminated unnecessary maintenance
  - Ensures performance of proposed sensors
  - Supports longer operational cycles, reduced maintenance requirements, and remote siting

- **Virtual sensor estimation**
  - Derive estimates of currently unmeasureable parameters

- **Potential applications in accident scenarios and transients**
  - Assess sensor measurement accuracy during accidents and transients
  - Provide necessary confidence in measurements during accidents using the virtual sensor concept

- **Signal validation as essential data preprocessing step for supervisory control and advanced health monitoring systems**
Crosscutting Benefits: AF, MPACT, UNFD

- Sensor reliability assessment for new sensor technologies
  - Ultrasonic sensors
  - Fiber optic sensors
  - Operation in harsh environments

- Real-time validation of large data streams for process monitoring in fuel reprocessing plants
  - Differentiating between sensor/detector faults and process changes

- Potential application to monitoring performance of sensors in long-term used fuel storage facilities
  - Applicability can be evaluated as sensor suites are designed and developed
Anticipated outcome for FY13

- Preliminary framework for uncertainty quantification
  - Model-neutral approach
  - Estimate uncertainty sources directly from data

Research areas for FY14-16

- Methodology for providing virtual sensor estimates and high-confidence signal validation
  - Integrate with UQ methodology
- Evaluation of the effects of emerging sensors, digital instrumentation, and wireless transmission
- Demonstration in an appropriate test-bed or facility will be necessary to ensure outcomes are tangible
Conclusion

Research focused on addressing high-impact technical gaps to developing a standardized framework for 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.)