Office Of Nuclear Energy
Sensors and Instrumentation
Annual Review Meeting

Embedded Instrumentation and Controls for Extreme Environments
Roger Kisner
Oak Ridge National Laboratory

September 16-18, 2014
Goal and Objectives

- Demonstrate performance/reliability improvements possible in major power reactor system components when sensors and controls are deeply integrated
- Embedded S&C enables faster control reaction and increased stability in the event of component failures compared with traditional control
- Makes stable inherently unstable configurations → smaller, lower mass, lower cost, more reliable
  - Railroad—AC traction drive locomotives enables 50% thrust increase
  - Industrial tools—Sawstop® prevents saw blade amputations
  - Aircraft/Aerospace—stabilizing fundamentally unstable wing configuration
  - Electric grid—Being Applied to Monitoring and Control of Power Distribution ($B)
- We are building a canned rotor coolant pump as a way to demonstrate embedded I&C in components—design, fabricate, and demonstrate
Project Overview (2)

Participants (first year, all ORNL staff)

- Roger Kisner—Principal Investigator, Control Systems, Sensor Systems, Magnetic Design, Electronics Design
- Alexander Melin—Control Systems, Mechanical Systems, Modeling and Simulation
- David Fugate—Control Systems, Electronics Design
- David Holcomb—Sensor Systems, Material Science
- Tim Burress—Sensor Systems, Motor Design, Electronics Design
- Dane Wilson—Material Science
- Summer Interns:
  - Electrical Engineering
  - Mechanical Engineering
  - Physics
FY-2013 Accomplishments

TASK 1: Model sensors and controls for canned rotor magnetics

- **PURPOSE:** magnetically suspended, canned rotor design cannot be operated without embedded S&C because of speed of response. Task was to understand dynamic mechanical system performance and potential degradations to create sensor, actuator, and control system.

- **WORK PRODUCT/DELIVERABLE:** Models and simulation results of sensors and controls for the magnetic suspension and drive system.


TASK 2: Assess methods of fabrication and assembly

- **PURPOSE:** high temperature operation requires special materials and sensors. Task was to understand materials, methods of fabrication, and methods of system assembly for machine design—sensors, actuators, and control systems.

- **WORK PRODUCT/DELIVERABLE:** Evaluation of effective methods to fabricate motor components and assemble as a working unit.

Working concurrently with ORNL research group investigating reluctance motors for transportation applications

- Hardware is being adapted for bench scale testing
- Investigating the effect of gap and rotor can material (Alloy N)

Invited paper in IEEE I&M Magazine*

- Lead article in June 2013 edition Advanced Instrumentation for Extreme Environments
- Discusses challenges of harsh environments for a canned rotor motor with embedded control

Results from Control Simulation

- Control strategy critical to optimize performance (simulation starts with rotor off-center)
  - *Left*: Mechanical springs (ex. journal bearings) oscillate due to shaft rotation and do not center the shaft
  - *Center*: PID control uncouples each axis and takes longer to reach equilibrium and has larger deviations from disturbances
  - *Right*: Linear Quadratic Regulator is a coupled control that quickly reaches equilibrium and is resilient to disturbances

- Simulation of 3-D rotor movement (graphs only show movement of rotor center-of-mass)
Year 1 — small scale development

- Design and build the bench-scale testbed (radial bearings and shaft position)
- Design and characterize sensors and actuators at high temperatures (especially induction type sensors)
- System identification and model validation
- Control system design and validation

Year 2 — loop-scale development

- Loop-scale testbed engineering analysis, design refinement, and finalization
- Finalize manufacturing and assembly drawings, requirements, and procedures
- Control system power electronics, hardware, algorithm, and software design and fabrication
- Loop-scale testbed manufacturing and assembly

Year 3 — install in water loop and test
Benefits of embedding are being validated and coordinated

- All nuclear power plant classes require coolant pumps
- Highly relevant demonstration in a representative environment

Pump seals and bearings are maintenance intensive

- Pump seals and bearings are have been historic source of problems in nuclear power applications
- Helium circulator seal leaks were a significant source of problems at Fort St. Vrain
- Pump seal leaks were root cause of Simi Valley sodium reactor accident
- Pumps possess large kinetic energy with potential for causing damage

What are the outcomes and measures of success

- Demonstration in a coolant loop system
- Future demonstration of embedded I&C in other reactor systems
- Demonstration that embedded I&C makes otherwise unattainable performance in nuclear power components possible
Research directly benefits DOE-NE R&D programs and initiatives
- SMRs, Na reactors, gas reactors, and fluoride salt reactors
- LWR Life Extension
- Advanced Reactors (high temperatures)
- Space Power Systems

Embedding concept is relevant to many components of a nuclear reactor
- Pumps, control rod drives, valves, circuit breakers, …
- Elevates components (and systems) to new levels of performance, stability, diagnostics, and prognostics
- Applies to primary systems and BOP components
- New reactor designs and retrofit

Resulting pump design is also applicable to solar thermal systems
Technology Impact

- Sensors and controls have not typically been embedded in nuclear power reactor components (compared with other industries)
  - Advanced I&C technologies were not available in the first nuclear era
  - Requires multi-disciplinary design effort — I&C, mechanical and electrical engineering, materials science, and systems engineering
  - Existing components have limitations for new reactor concepts

- Required new component concepts may be inherently unstable
  - Compact size
  - Less bulk material to absorb transients
  - Continuous high temperature operation

- Embedded I&C stabilizes otherwise unstable configurations
  - Intimate real-time control
  - Reporting of degradation
  - Appropriate responses to failure and degradation events
  - Opportunity for fault-tolerant control
Advancing the state-of-the-art in nuclear systems

- Traditional approach to large component design is to include mass, large margins, and tolerate inefficiency as cost of doing business
- Close coupling of I&C with electromechanical system components permits design with minimal mass and appropriate margins leading to lower cost, higher performance, and improved reliability (modern jet engines have experienced a 1000X reliability improvement with embedded I&C)

Embedded I&C can help DOE-NE meet three of four primary research objectives

1. Develop technologies and other solutions that can improve the reliability, sustain the safety, and extend the life of current reactors
2. Develop improvements in the affordability of new reactors to enable nuclear energy to help meet the Administration's energy security and climate change goals
3. Develop sustainable nuclear fuel cycles
4. Understand and minimize the risks of nuclear proliferation and terrorism
Technology affects the nuclear industry

- Working system demonstration provides needed confidence to allow designers to rely on integrated measurements and controls to provide robustness and efficiency
- Embedding I&C where they have not been before in major components of a nuclear power plant changes capabilities and takes I&C to new level
- Integrated measurement and controls practices can be applied to many component types
- More reliable and efficient motors, pumps, valves, circuit breakers, control rod drives, …
By successfully demonstrating the performance, reliability, and cost benefits of embedded I&C on a relevant prototypic reactor component, confidence is realized that can lead to major improvements in reactor system components for future plants:

- Improve the reliability, sustain the safety, and extend the life of current reactors
- Develop improvements in the affordability of new reactors to enable nuclear energy to help meet the Administration’s energy security and climate change goals
Back Up Slides
Embedded I&C Is Being Applied to Monitoring and Control of Power Distribution Systems

- Embedded I&C will transform a static system into a dynamic system with distributed control—control pushed to the outer limits of system
  - Distributed control — large distances
  - High speed control response
  - Improved reliability (elimination of single point failure)

- Potentially save $billions annually by reducing occurrences of brown-outs and black-outs
# Schedule

## Year 1: Bench-scale embedded sensor and controls development

<table>
<thead>
<tr>
<th>Activity</th>
<th>Start Date: 10/1/2014</th>
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<tbody>
<tr>
<td>Design and build the bench-scale testbed</td>
<td>10/1/2014 to 3/1/2015</td>
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<tr>
<td>Design and characterize sensors and actuators at high temperatures</td>
<td>3/1/2015 to 6/1/2015</td>
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<tr>
<td>System identification and model validation</td>
<td>3/1/2015 to 5/1/2015</td>
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<tr>
<td>Control system design and validation</td>
<td>3/1/2015 to 9/1/2015</td>
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<tr>
<td>Sensor report and control design report generation</td>
<td>9/1/2015 to 10/1/2015</td>
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## Year 2: Loop-scale embedded I&C testbed design

<table>
<thead>
<tr>
<th>Activity</th>
<th>Start Date: 10/1/2015 to 4/1/2016</th>
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<tbody>
<tr>
<td>Loop-scale testbed engineering analysis, design refinement, and finalization</td>
<td>10/1/2015 to 4/1/2016</td>
</tr>
<tr>
<td>Finalize manufacturing and assembly drawings, requirements, and procedures</td>
<td>4/1/2016 to 5/1/2016</td>
</tr>
<tr>
<td>Control system power electronics, hardware, algorithm, and software design and fabrication</td>
<td>1/1/2016 to 5/1/2016</td>
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<tr>
<td>Loop-scale testbed manufacturing and assembly</td>
<td>5/1/2016 to 9/1/2016</td>
</tr>
<tr>
<td>Loop-scale embedded I&amp;C design report generation</td>
<td>9/1/2016 to 10/1/2016</td>
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## Year 3: Loop integration and system performance testing

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<tr>
<th>Activity</th>
<th>Start Date: 10/1/2016 to 2/1/2017</th>
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<tr>
<td>Integrate testbed with a water loop</td>
<td>10/1/2016 to 2/1/2017</td>
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<tr>
<td>Development and documentation of performance metrics and test procedures</td>
<td>11/1/2016 to 2/1/2017</td>
</tr>
<tr>
<td>Performance testing on integrated system</td>
<td>2/1/2017 to 9/1/2017</td>
</tr>
<tr>
<td>Final report generation</td>
<td>9/1/2017 to 10/1/2017</td>
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The Light Water Reactor Sustainability (LWRS) will benefit from this R&D through
Retrofit of components having embedded I&C for extended life, high reliability, and efficiency

The Advanced Small Modular Reactor (SMR) Program will benefit from this R&D through
Design of components that are cost effective, low maintenance, and reliable

Advanced Reactor Concepts (ARC) and Next Generation Nuclear Plant (NGNP) programs will benefit from this R&D through
Design of components that operate efficiently and reliably in extreme environments

The Fuel Cycle Technologies (FCT) program could indirectly benefit from this R&D through
Design of components that are low maintenance and long lived in harsh environments
Technology being used by Chinese reactor designers

- UT-Battelle work on salt reactor development starting in October sponsored by Shanghai Institute of Applied Physics—eventually will use embedded technology
- Prototype helium fan for China’s HTR-PM high-temperature gas-cooled reactor completed testing—electromagnetic bearings

NRC is concerned about safety aspects of embedded systems