



U.S. DEPARTMENT OF
ENERGY

Nuclear Energy

**Office Of Nuclear Energy
Sensors and Instrumentation
Annual Review Meeting**

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

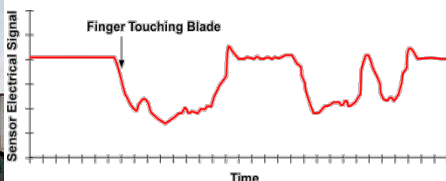
September 16-18, 2014



Project Overview

■ 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



Sawstop® Blade
Current Signal

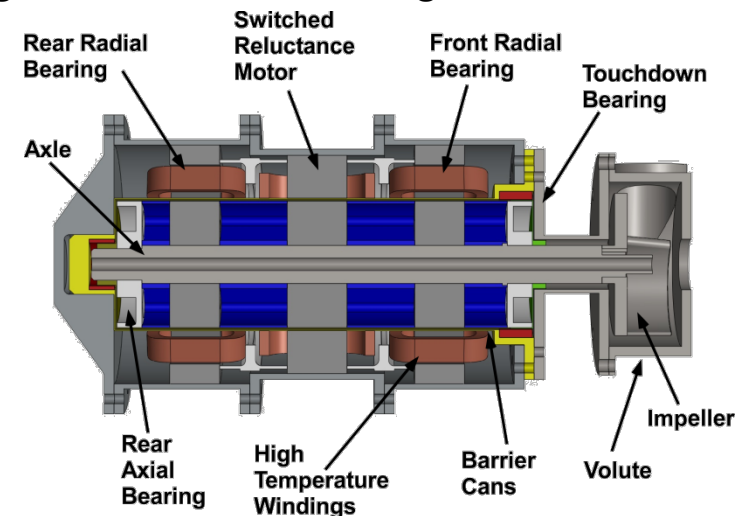




Project Overview (2)

■ 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
- **MILESTONE:** September 30, 2013, report *Embedded Sensors and Controls to Improve Component Performance and Reliability – System Dynamics Modeling and Control System Design*, ORNL/TM-2013/415

■ 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
- **MILESTONE:** July 29, 2013, report *Evaluation of Manufacturability of Embedded Sensors and Controls with Canned Rotor Pump System*, ORNL/TM-2013/269



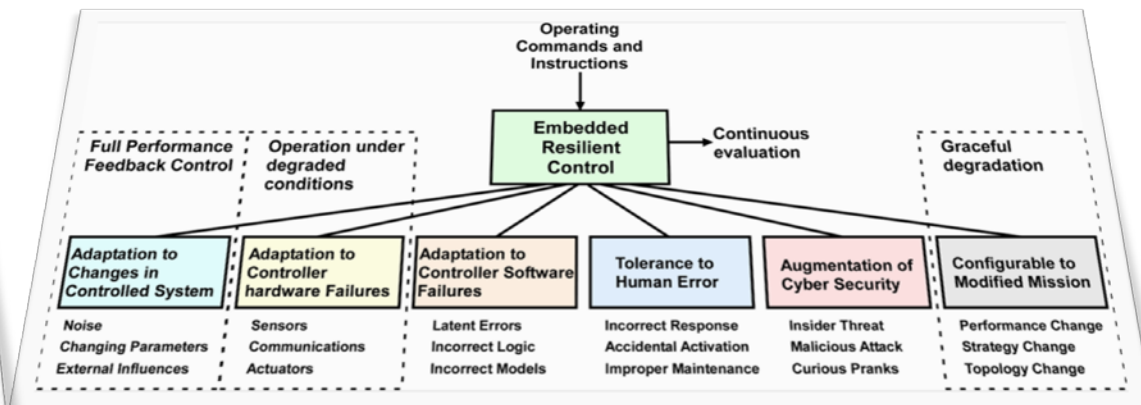
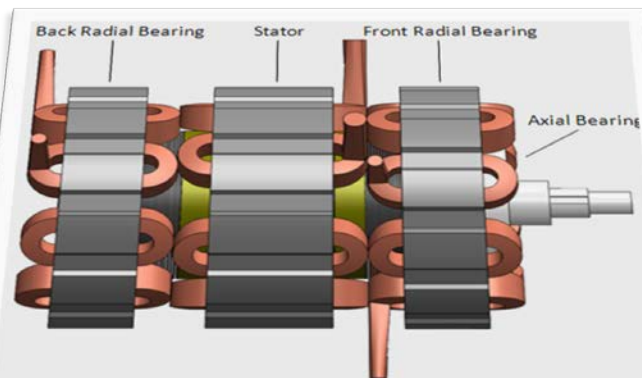
FY-2013 Accomplishments (2)

■ 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

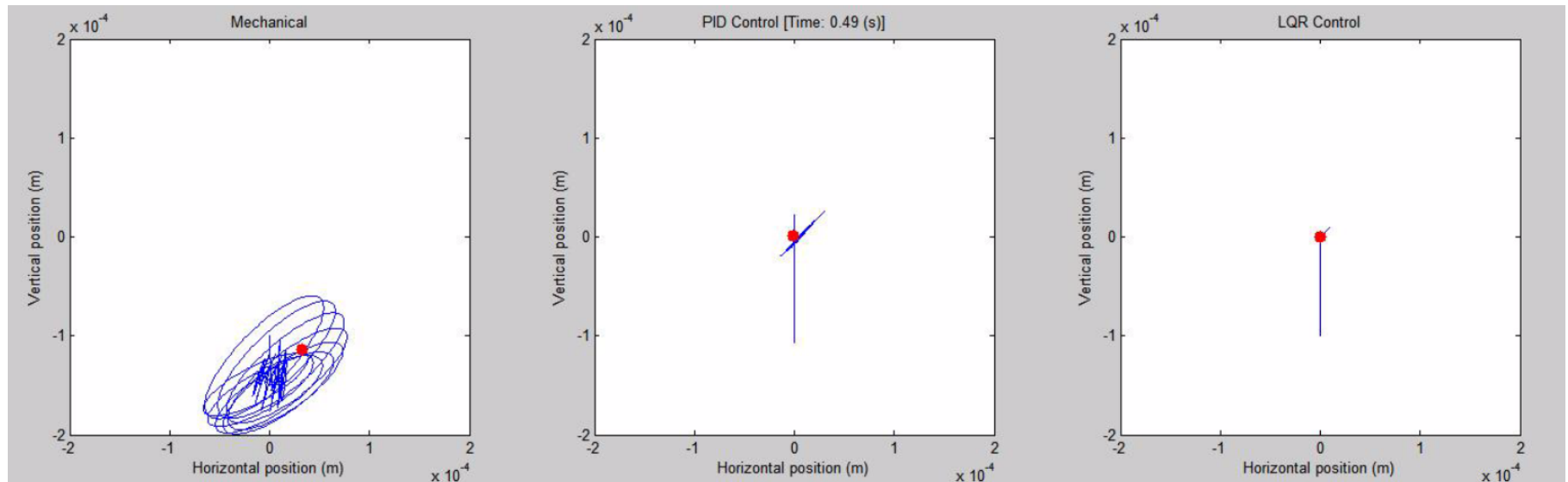


* A. Melin, R. Kisner, and D. Fugate, "Advanced Instrumentation for Extreme Environments," IEEE I&M Magazine, Vol.16, No. 3, June 2013.



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)**





Planned Activities

■ 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



Crosscutting Benefits

■ 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



Crosscutting Benefits (2)

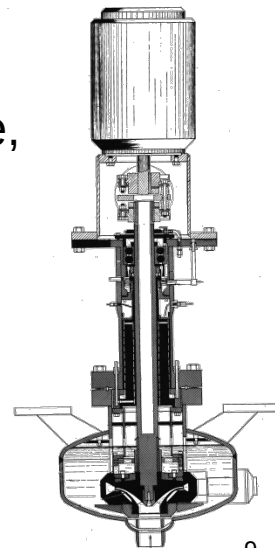
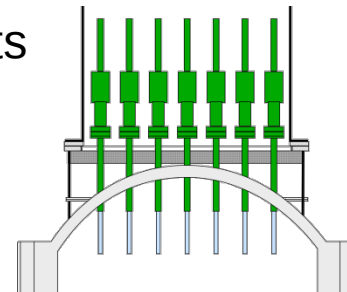
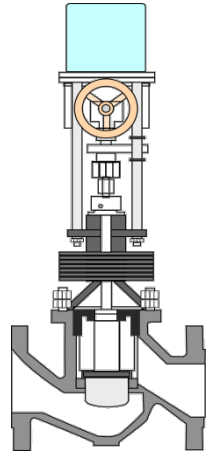
■ Research directly benefits DOE-NE R&D programs and initiatives

- 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

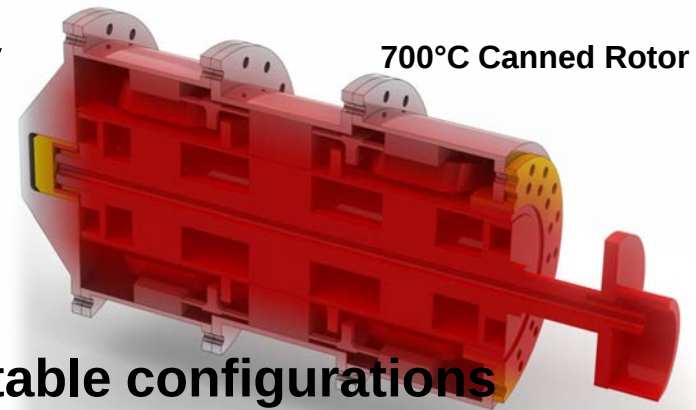
■ Resulting pump design is also applicable to solar thermal systems





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





Technology Impact (2)

■ 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

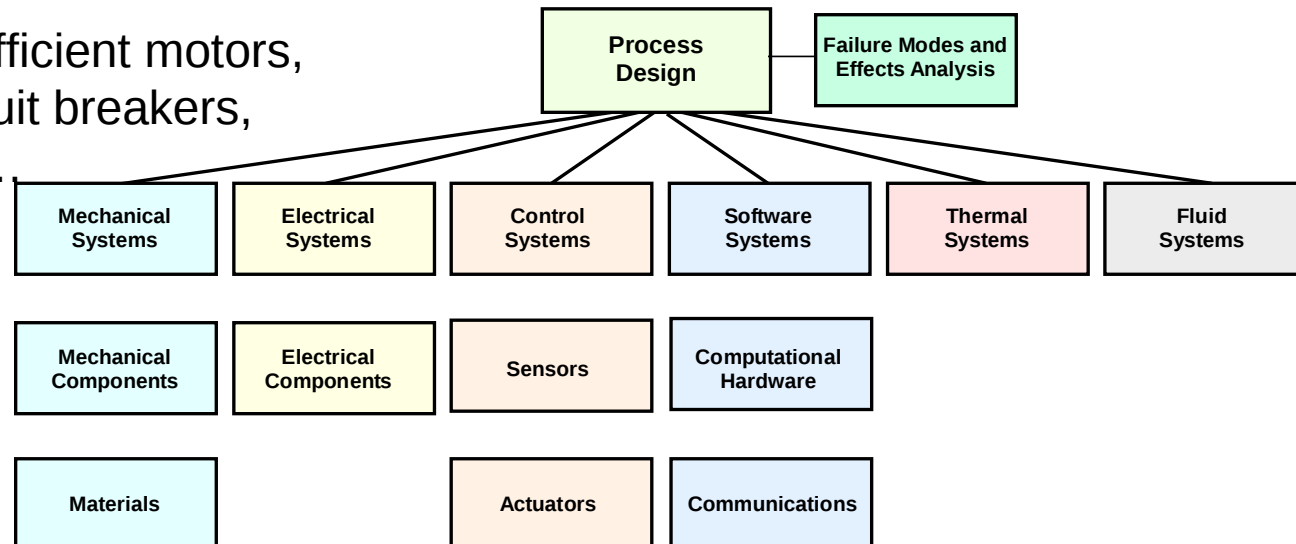
- ✓ 1. Develop technologies and other solutions that can improve the reliability, sustain the safety, and extend the life of current reactors
- ✓ 2. Develop improvements in the affordability of new reactors to enable nuclear energy to help meet the Administration's energy security and climate change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



Technology Impact (3)

■ 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, ...





Conclusion

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- **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



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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: <i>Bench-scale embedded sensor and controls development</i>		Start Date: 10/1/2014
Design and build the bench-scale testbed		10/1/2014 to 3/1/2015
Design and characterize sensors and actuators at high temperatures		3/1/2015 to 6/1/2015
System identification and model validation		3/1/2015 to 5/1/2015
Control system design and validation		3/1/2015 to 9/1/2015
Sensor report and control design report generation		9/1/2015 to 10/1/2015
Year 2: <i>Loop-scale embedded I&C testbed design</i>		
Loop-scale testbed engineering analysis, design refinement, and finalization		10/1/2015 to 4/1/2016
Finalize manufacturing and assembly drawings, requirements, and procedures		4/1/2016 to 5/1/2016
Control system power electronics, hardware, algorithm, and software design and fabrication		1/1/2016 to 5/1/2016
Loop-scale testbed manufacturing and assembly		5/1/2016 to 9/1/2016
Loop-scale embedded I&C design report generation		9/1/2016 to 10/1/2016
Year 3: <i>Loop integration and system performance testing</i>		
Integrate testbed with a water loop		10/1/2016 to 2/1/2017
Development and documentation of performance metrics and test procedures		11/1/2016 to 2/1/2017
Performance testing on integrated system		2/1/2017 to 9/1/2017
Final report generation		9/1/2017 to 10/1/2017



Crosscutting Benefits (3)

- **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 Impact (4)

■ 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

