U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Office Of Nuclear Energy Sensors and Instrumentation Annual Review Meeting

Embedded Instrumentation and Controls for Extreme Environments

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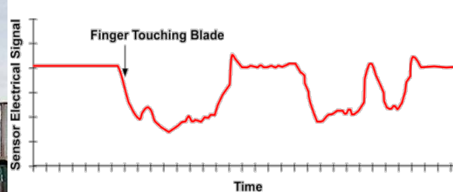
Project Overview

■ 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

Loco AC Traction Motors



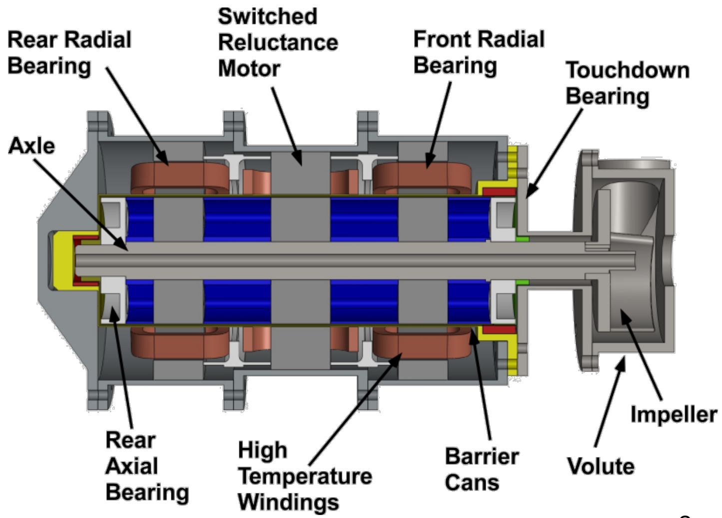
Sawstop® Blade Current Signal

Delta Wing Aircraft

Dynamic System with Distributed Control

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

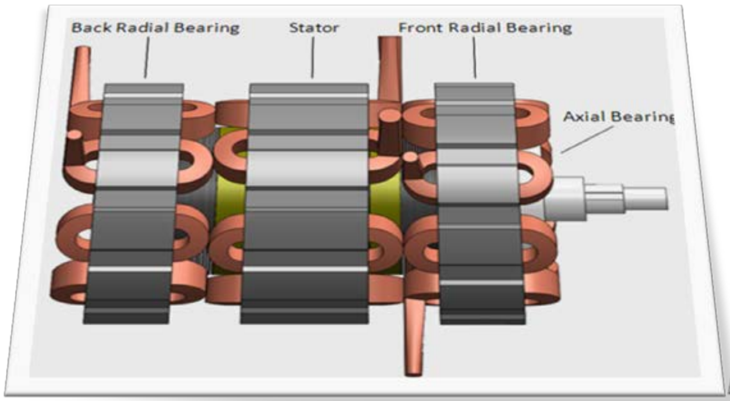


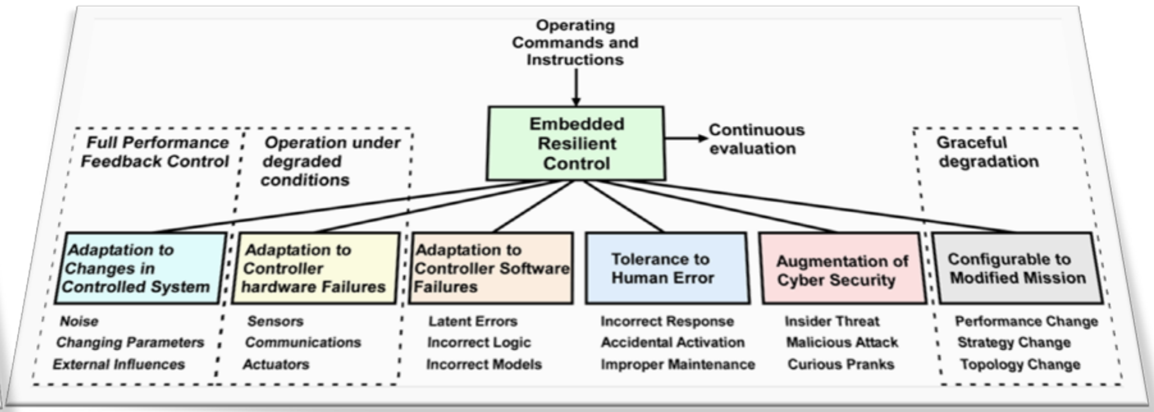
FY-2013 Accomplishments

- **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.

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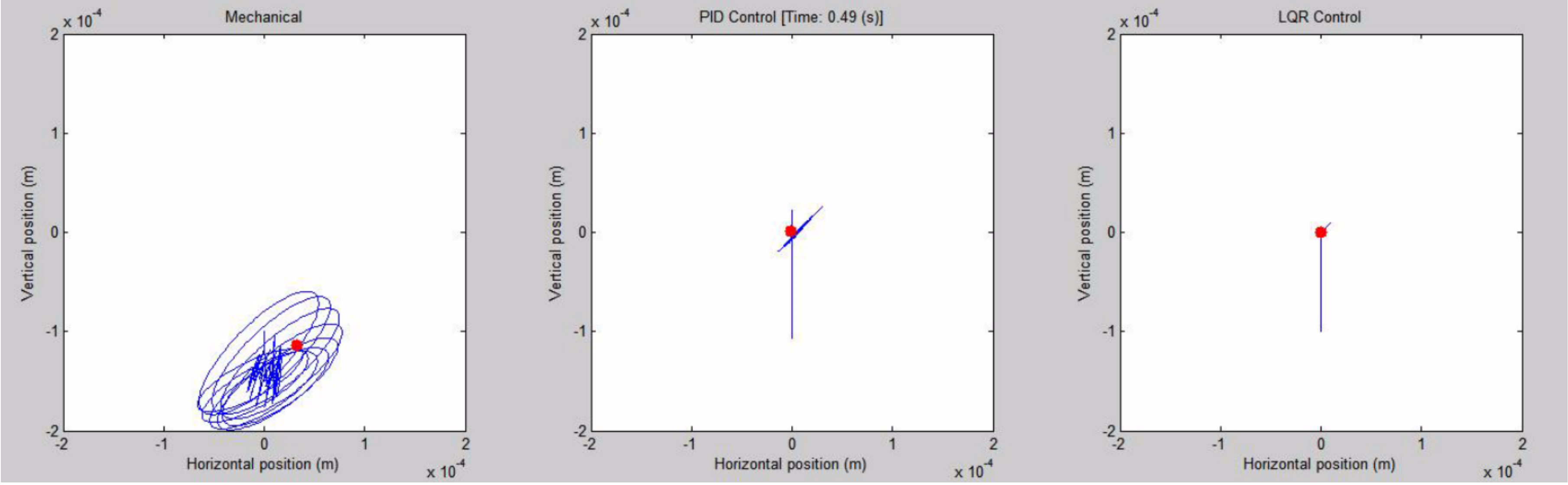
Results from Control Simulation

- **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

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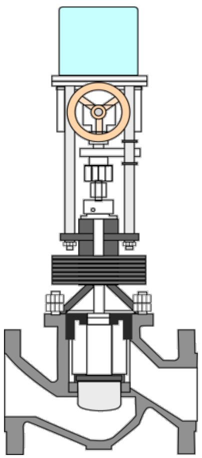
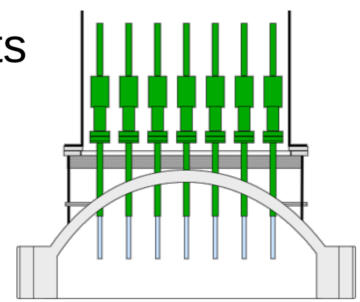
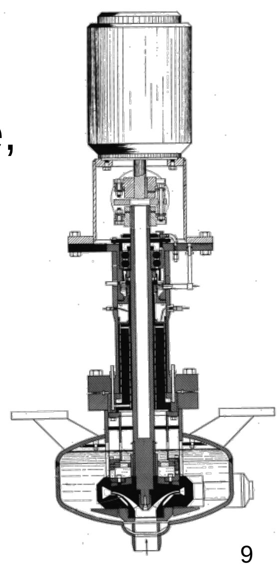
Crosscutting Benefits (2)

- **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**





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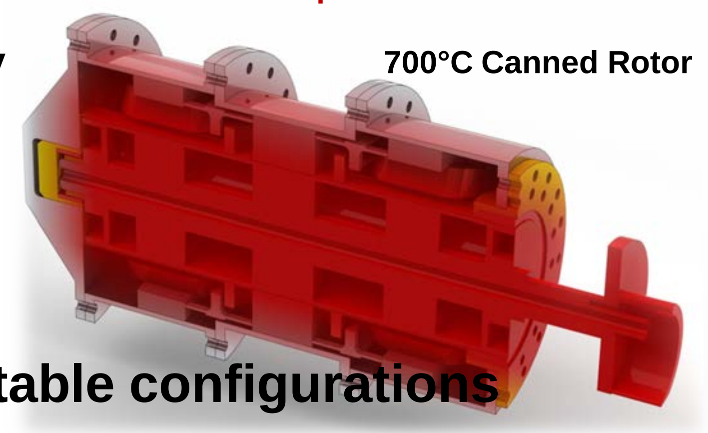
Technology Impact

- **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



700°C Canned Rotor

- **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

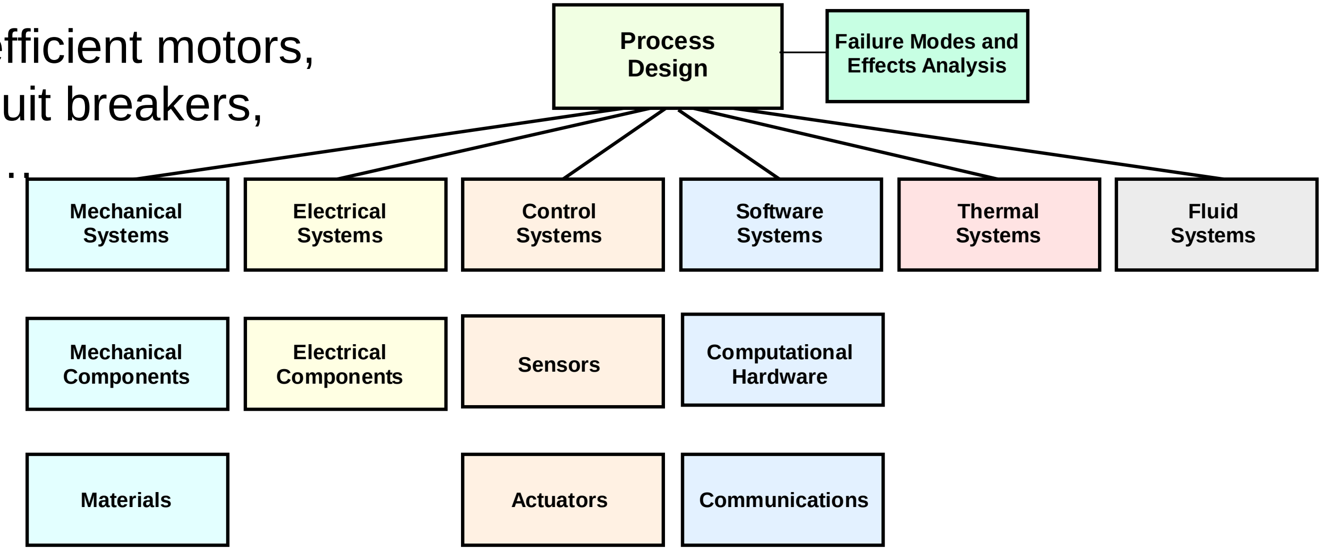
✓ 3. Develop sustainable nuclear fuel cycles

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

- **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**

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Schedule

Year 1: *Bench-scale embedded sensor and controls development*	**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: *Loop-scale embedded I&C testbed design*	
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: *Loop integration and system performance testing*	
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 10/1/217

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**