U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Clean. Reliable. Nuclear.

Demonstration of Embedded I&C

Advanced Sensors and Instrumentation Annual Webinar

October 31 – November 1, 2018

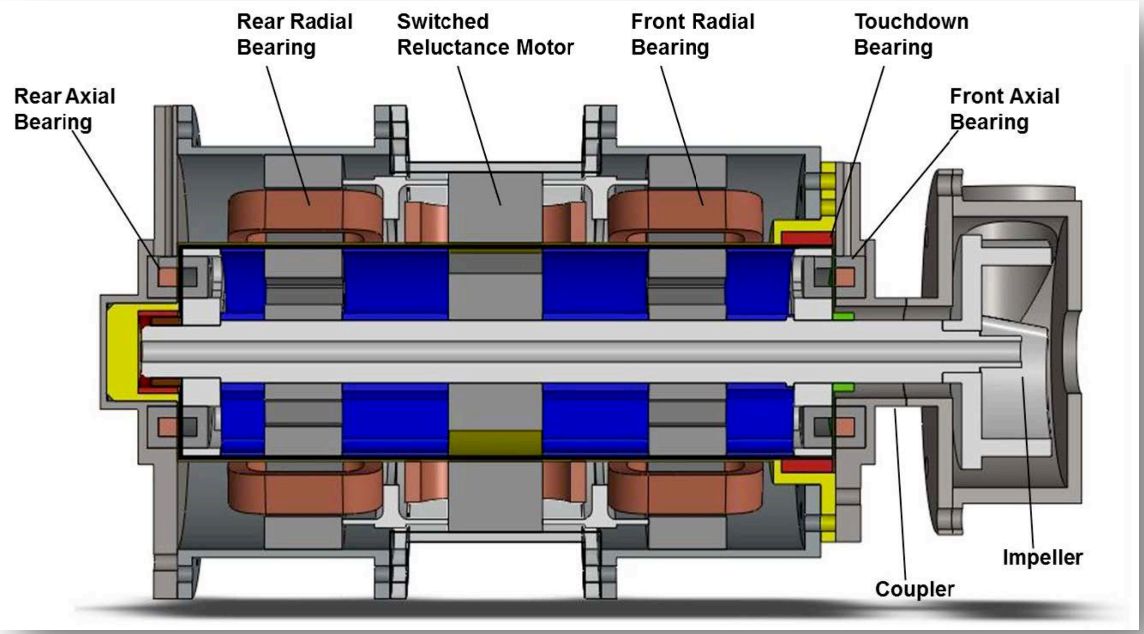
Dr. Alexander Melin
Oak Ridge National Laboratory

Project Overview

- Overview of Previous Work
  - High Temperature Molten Salt Pump Conceptual Design
  - Manufacturability Analysis
  - Component Reliability Analysis
  - Modeling and Control Design
  - Bench-top magnetic bearing testbed
  - Loop-scale magnetic bearing testbed

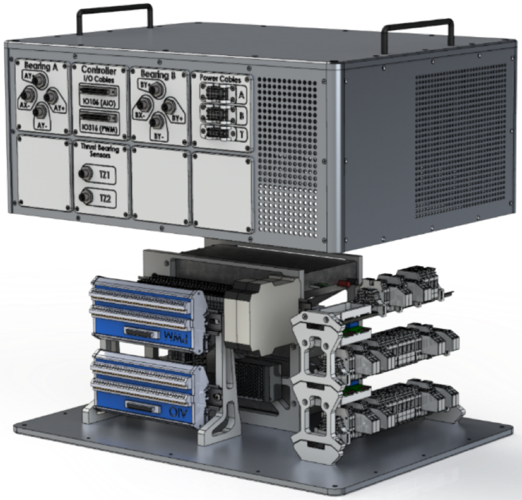
Project Overview

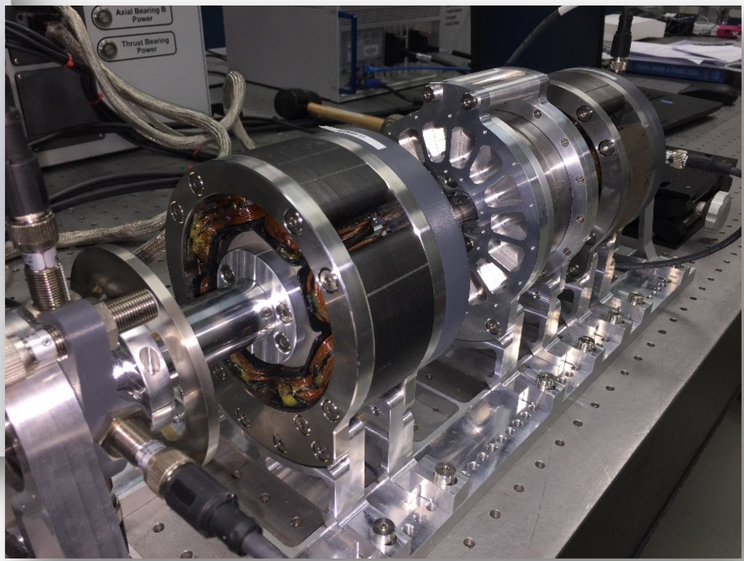
- Overview of Previous Work
  - Conceptual high temperature molten salt pump design
    - Material studies and selection
    - System requirements and design basis
    - Electrical and magnetic design
    - High temperature wiring
    - Environmental conditions
    - Sensors and controls
    - Reliability



Project Overview

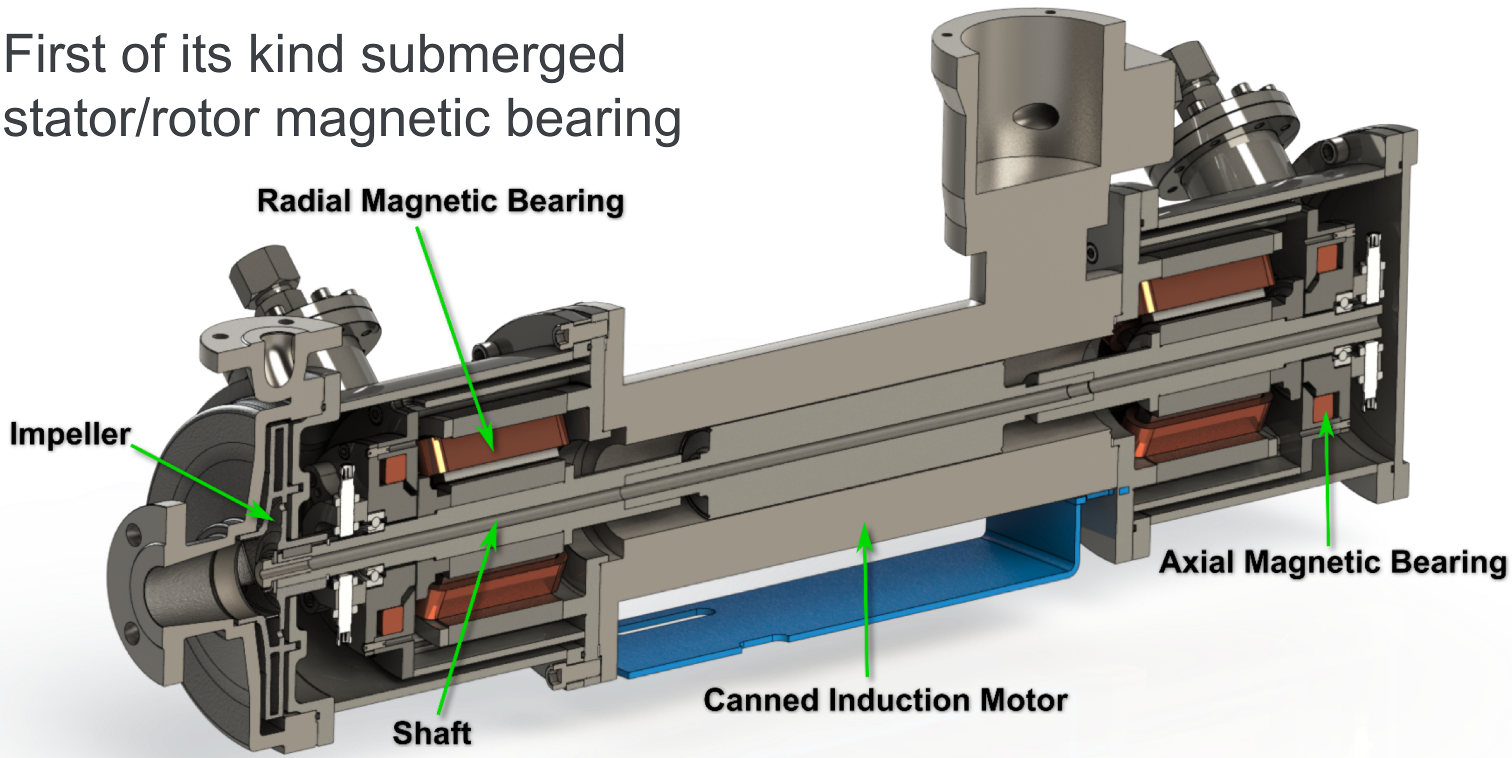
- Overview of Previous Work
  - Bench-top magnetic bearing testbed
    - 30 A max coil current, 24 V
    - 500 N max force





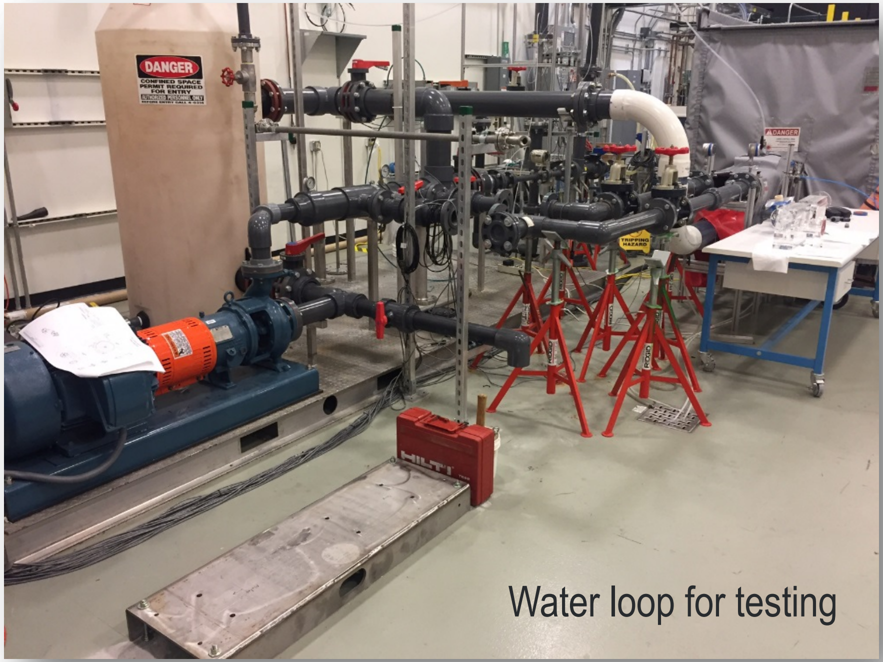
Project Overview

- Overview of Previous Work
  - Loop-scale magnetic bearing testbed
  - 30 A max coil current, 24 V
  - 2000 N max force
  - First of its kind submerged stator/rotor magnetic bearing



Project Overview

- Overview of Previous Work
  - Loop-scale magnetic bearing testbed
  - Problems with commercial PWM boards in power supply



Water loop for testing

- Incorrectly wired ground
- Prevented operation in bipolar mode (-24 V to 24 V)
- Like a car with accelerator but no brakes

Project Overview

- Goals and Objectives
  - Increase nuclear industry awareness of the advantages of embedded I&C through technical posters, presentations, reports, and peer-reviewed publications.
  - Design a custom controllable power supply for the ORNL submerged magnetic bearing testbed to improve the current response.
  - Synthesize, program, and test a new stabilizing feedback controller using the new power supplies.
  - Install testbed in a water test loop.
  - Experiments
    - System identification with both dry and wet stator/rotor for A/B rotordynamics comparison.
    - Pump performance comparison (power, energy, and pressure vs. flow)
    - Coast down time vs. static shaft position.

Project Overview

- Goal and Objective
- Participants
  - Dr. Alexander Melin
  - Kyle Reed
  - Dr. Aravind Mikkilineni
  - Roger Kisner
- Revised Schedule

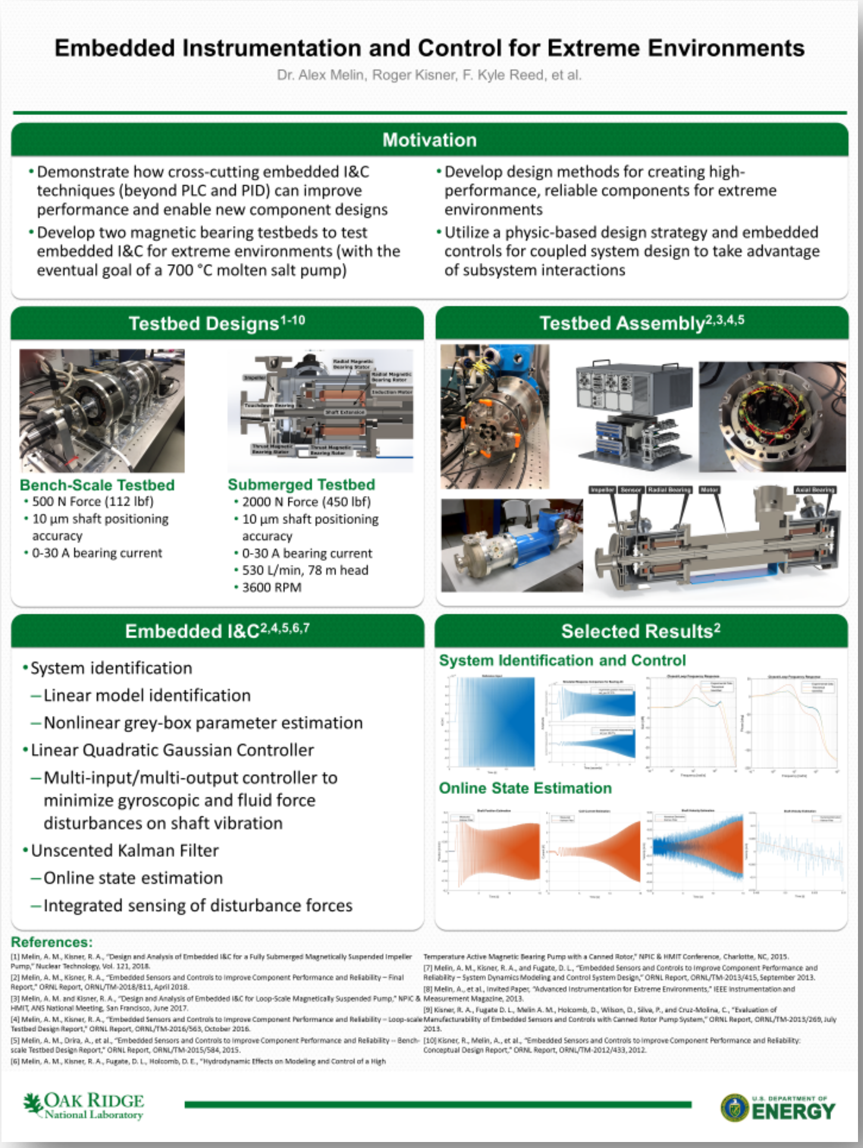
Tasks	Description	May	June	July	August	September	October	November	December
Task 1	Design and Fabricate PWM Modules to Operate in Bi-Polar Mode								
Task 2	Program the Stabilizing Controller								
Task 3	Install Pump in Loop								
Task 4	Conduct Experiments								
Task 5	Prepare Report and Present Poster at Meeting								

Accomplishments

- Milestones
  - Design and fabricate bipolar model controllable voltage source
  - Program stabilizing controller for magnetic bearing levitation
  - Install testbed in water loop
  - Conduct experiments with both dry and submerged rotor/stator
- Deliverables
  - High-performance high-current open-source controllable voltage supply design
  - Peer-reviewed publication on the impact of fluid forces on rotordynamics
  - Report on the results of the experimental testing and analysis of the results
  - Power presentation at the Digital Environment for Advanced Reactors Workshop (June 5-6, 2018)

Accomplishments

- Outcomes
  - Poster presentations at Digital Environments for Advanced Reactors Workshop
  - Engaged with industry, academia, and national laboratories to
    - Exchange information on currently available technologies .
    - Identify technical gaps needed for advanced reactors.

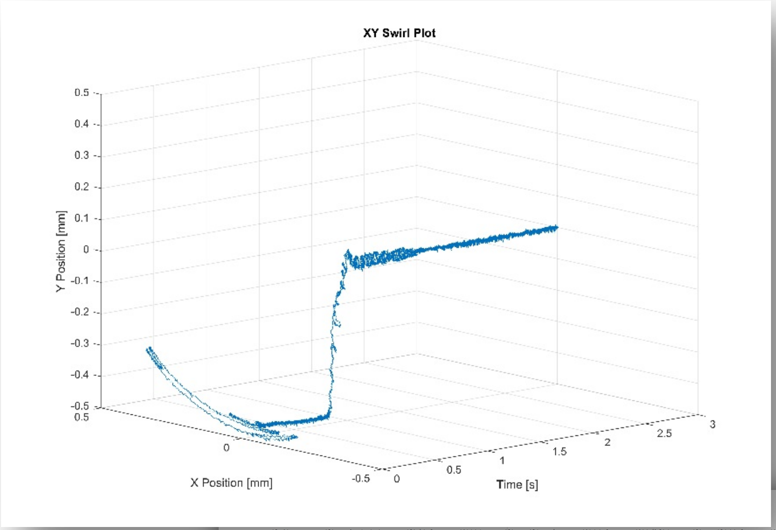


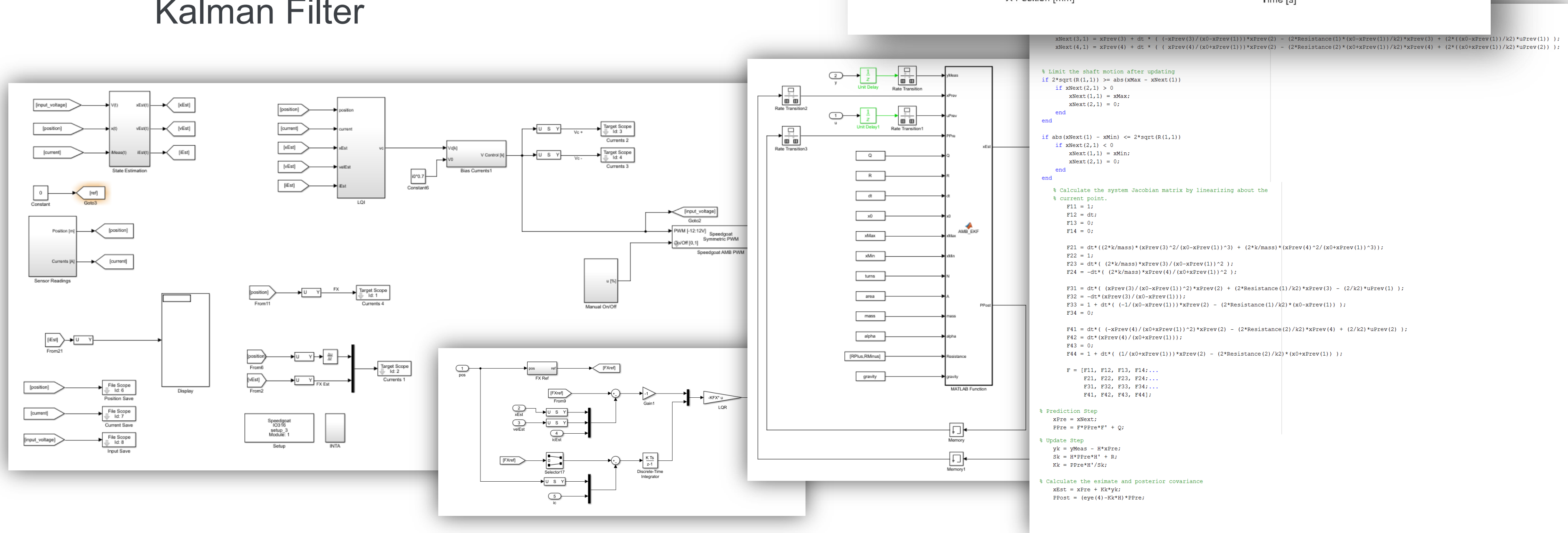
Accomplishments

- Controllable Power Supply
  - Designed and fabricated
  - Electrical design, packaging, cables, and graphics

Accomplishments

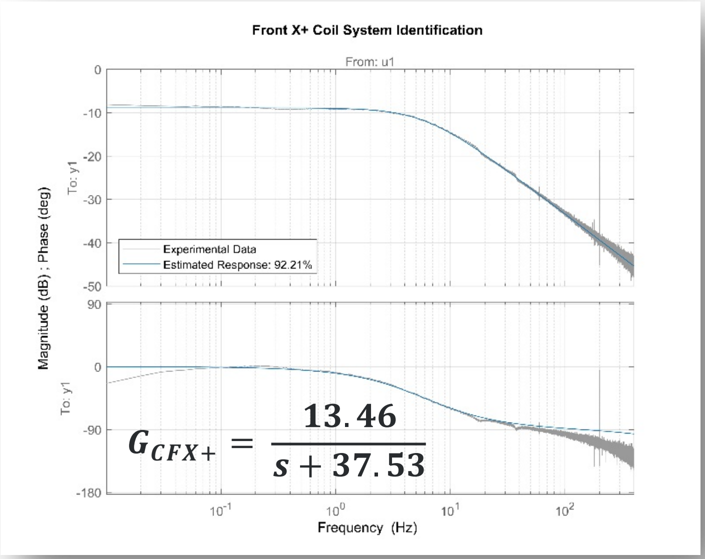
- Stabilizing Feedback Controller Synthesized
  - Cascade design
  - Simulink and real-time toolbox
  - 10 kHz control loop-speed
  - 700 Hz control current bandwidth
  - 150 Hz shaft motion bandwidth
  - State estimation using custom Extended Kalman Filter

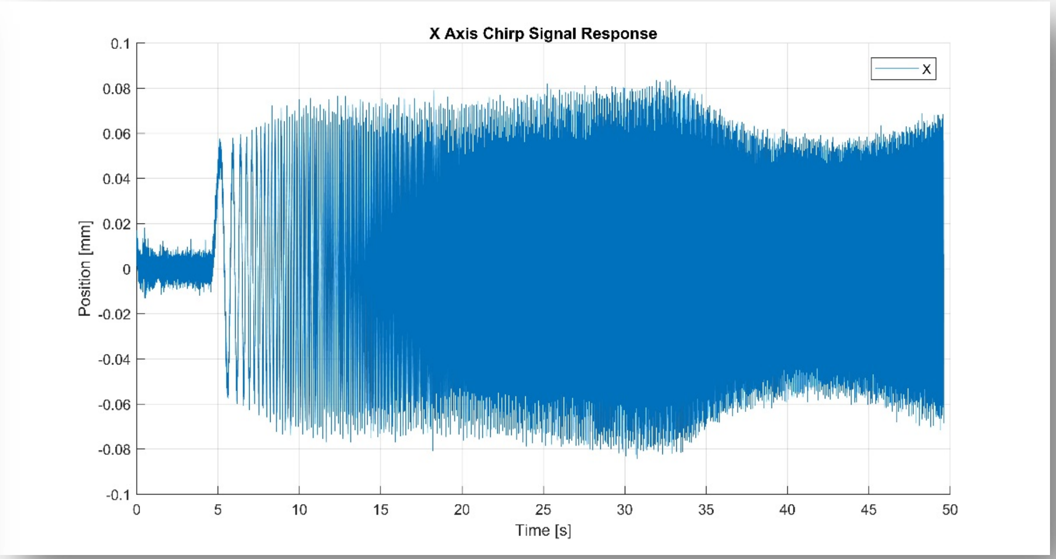




Accomplishments

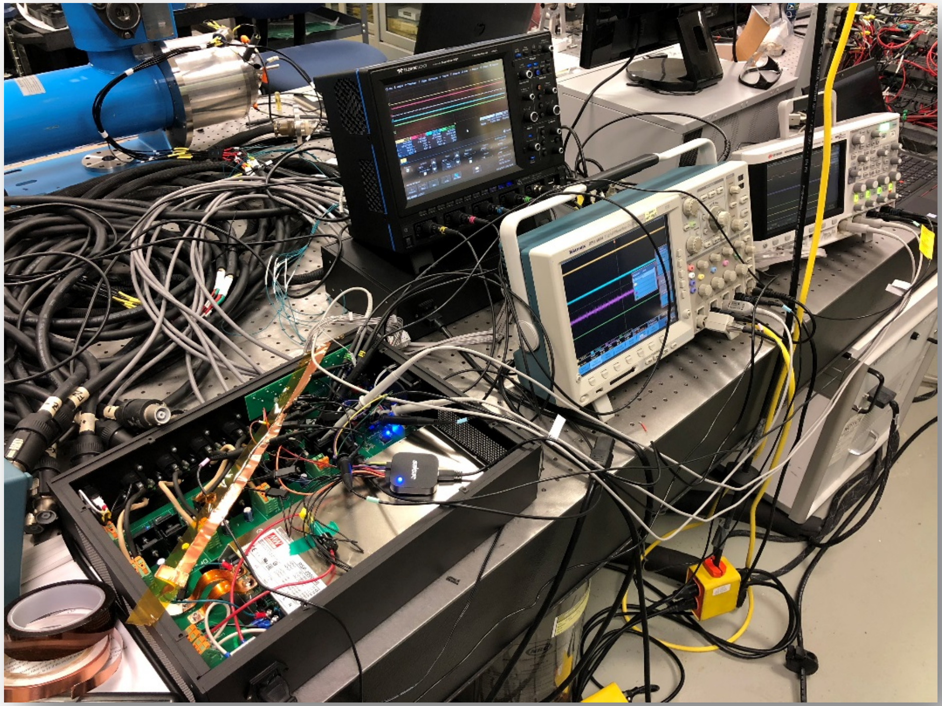
- Initial System Identification Data Captured
  - Magnetic bearing/power supply dynamics
  - Horizontal axis bearing dynamics
    - Two power supply channel PWM controllers failed during these experiments
    - Currently identifying the root cause and repairing the power supplies.





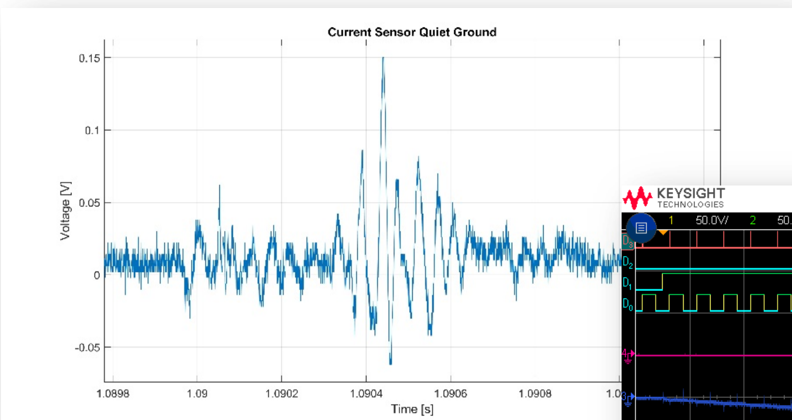
Accomplishments

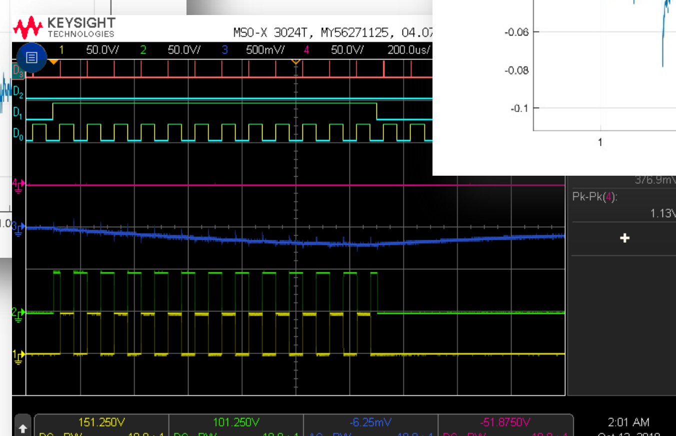
- Power supply fault diagnosis and correction
  - Measured 18 points in the power circuit
  - Large inductances and energy in magnetic bearing coils causing capacitive noise in TTL lines and grounds
  - Some floating grounds picked up excessive noise
  - Current sensor output low-pass filter cutoff frequency greatly increased by the ground noise
    - Caused large noise in the current feedback controller output

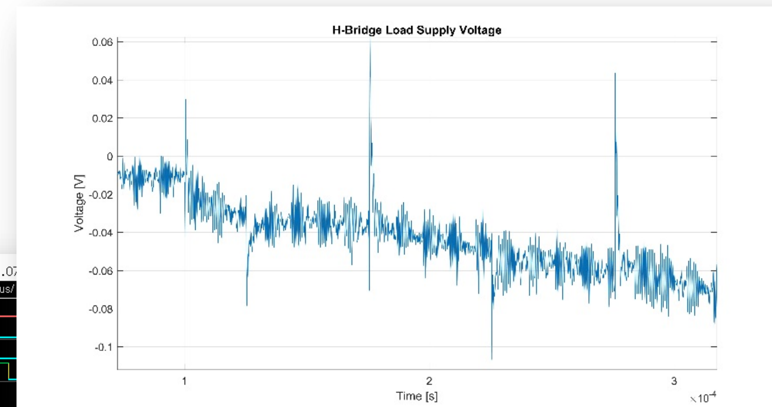


Accomplishments

- Improving the System Performance
  - Reducing ground noise
  - Fixing current sensor low-pass filter
  - Adding hardware filters to reduce capacitive coupling
  - Increased sensor sample rates in software by 20X
  - Increased PWM frequency by 5X







Accomplishments

- ## Papers

1. Melin, A. M. and Kisner, R. A., "Design and Analysis of Embedded I&C for Loop-Scale Magnetically Suspended Pump," *Nuclear Technology*, Vol. 202, Issue 2-3, pp. 180-190, April 2018.
2. Melin, A. M. and Kisner, R. A., "Design and Analysis of Embedded I&C for Loop-Scale Magnetically Suspended Pump," NPIC & HMIT, ANS National Meeting, San Francisco, April 2018.
3. Melin, A. M. and Kisner, R. A., "Design and Analysis of Embedded I&C for Loop-Scale Magnetically Suspended Pump," NPIC & HMIT, ANS National Meeting, San Francisco, June 2017.
4. Melin, A. M., Kisner, R. A., Fugate, D. L., Holcomb, D. E., "Hydrodynamic Effects on Modeling and Control of a High Temperature Active Magnetic Bearing Pump with a Canned Rotor," NPIC & HMIT Conference, Charlotte, NC, 2015.
5. Melin, A., et al., *Invited Paper,* "Advanced Instrumentation for Extreme Environments," *IEEE Instrumentation and Measurement Magazine*, 2013.

- ## Technical Reports

1. Melin, A. M., Kisner, R. A., Blaise, B., Meert, C., Reed, F. K., "Embedded Sensors and Controls to Improve Component Performance and Reliability – Final Report," *ORNL Report,* ORNL/TM-2018/811, April 2018.
2. Melin, A. M., Kisner, R. A., "Embedded Sensors and Controls to Improve Component Performance and Reliability – Loop-scale Testbed Design Report," *ORNL Report,* ORNL/TM-2016/563, October 2016.
3. Melin, A. M., et al., "Embedded Sensors and Controls to Improve Component Performance and Reliability -- Bench-scale Testbed Design Report," *ORNL Report,* ORNL/TM-2015/584, 2015.
4. Melin, A. M., Kisner, R. A., and Fugate, D. L., "Embedded Sensors and Controls to Improve Component Performance and Reliability – System Dynamics Modeling and Control System Design," ORNL Report, ORNL/TM-2013/415, September 2013.
5. Kisner, R. A., Fugate D. L., Melin A. M., Holcomb, D., Wilson, D., Silva, P., and Cruz-Molina, C., "Evaluation of Manufacturability of Embedded Sensors and Controls with Canned Rotor Pump System," ORNL Report, ORNL/TM-2013/269, July 2013.
6. Kisner, R., Melin, A., et al., "Embedded Sensors and Controls to Improve Component Performance and Reliability: Conceptual Design Report," *ORNL Report*, ORNL/TM-2012/433, 2012.

Technology Impact

- Nuclear reactor components need to operate reliably in extreme environments.
  - Embedded I&C in reactor components will
    - Improve reliability and performance
    - Enable real-time health monitoring and predictive maintenance
    - Gather data for improved reactor systems and component models
    - *Enable devices to operate in more extreme environments*
- This technology is the foundation for ultra-high temperature (> 450 C, 842 F) electromagnetic devices (pumps, motors, magnetic bearings, inductive position sensors…)
  - These will be critical components for new reactor designs such as molten salt reactors.

Technology Impact

- Nuclear Industry Impacts
  - Canned rotor pump designs can reduce pump size, cost, and maintenance.
  - Ultra-high temperature components can operate in more reactor environments.
  - Show improvements from embedded I&C
- Commercialization
  - ORNL is partnering with Hayward Tyler and ARPA-E to develop a canned rotor molten salt pump with the following components operating at 650-700 C
    - Magnetic bearings for shaft levitation
    - Synchronous reluctance motor for shaft rotation
    - Radial, axial, and rotational position sensors
    - Electromagnetic coils

Conclusion

- Developed new high-current high-bandwidth controllable power supply for ORNL submerged magnetic bearing testbed.
- Developed a stabilizing controller for the testbed and performed system identification experiments.
- Engaged with nuclear industry showcase current embedded I&C research and discuss future implementation of digital I&C in nuclear reactors.
- Successfully won an ARPA-E research grant with Hayward Tyler and TEUSA to develop and test a 650-700 C molten salt pump based on this research.

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For any future questions please contact me at **melina@ornl.gov**