



Demonstration of Embedded I&C

**Advanced Sensors and Instrumentation
Annual Webinar**

October 31 – November 1, 2018

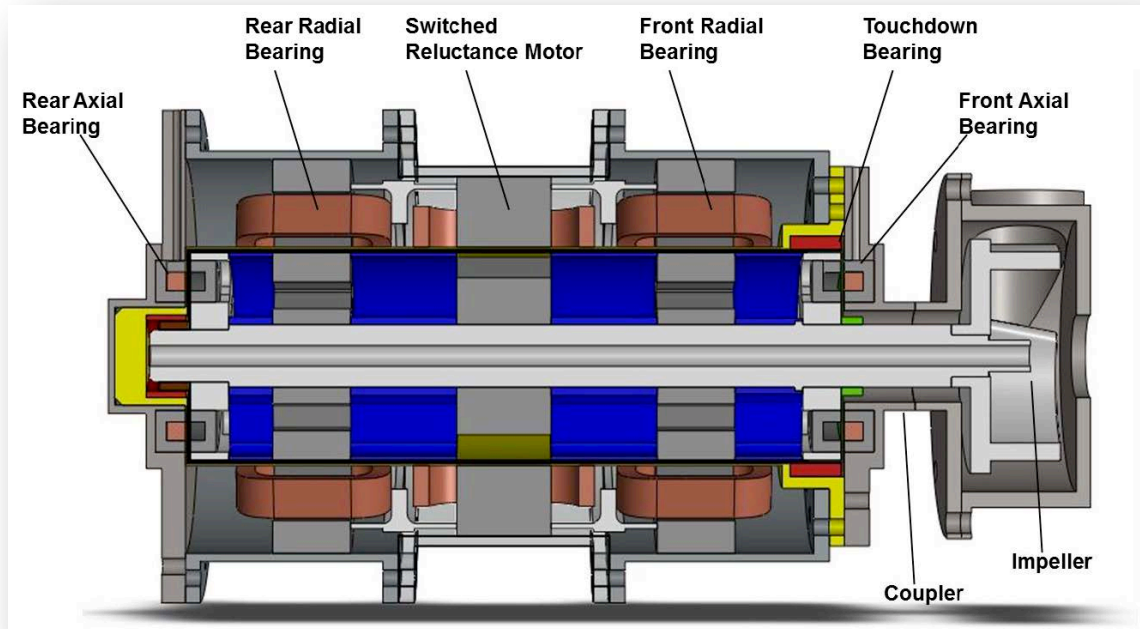
Dr. Alexander Melin
Oak Ridge National Laboratory

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

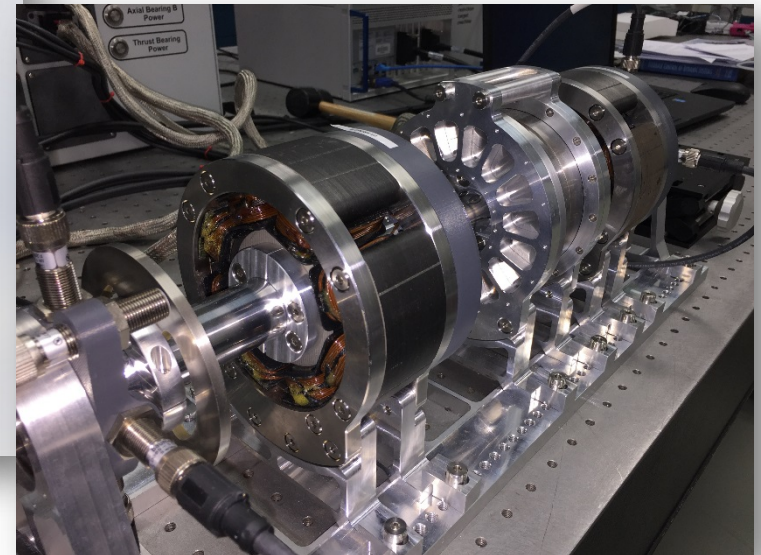
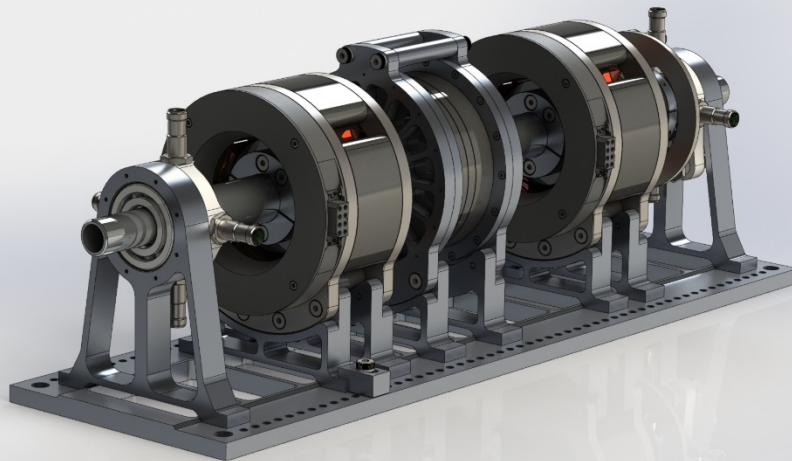
Project Overview

- 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



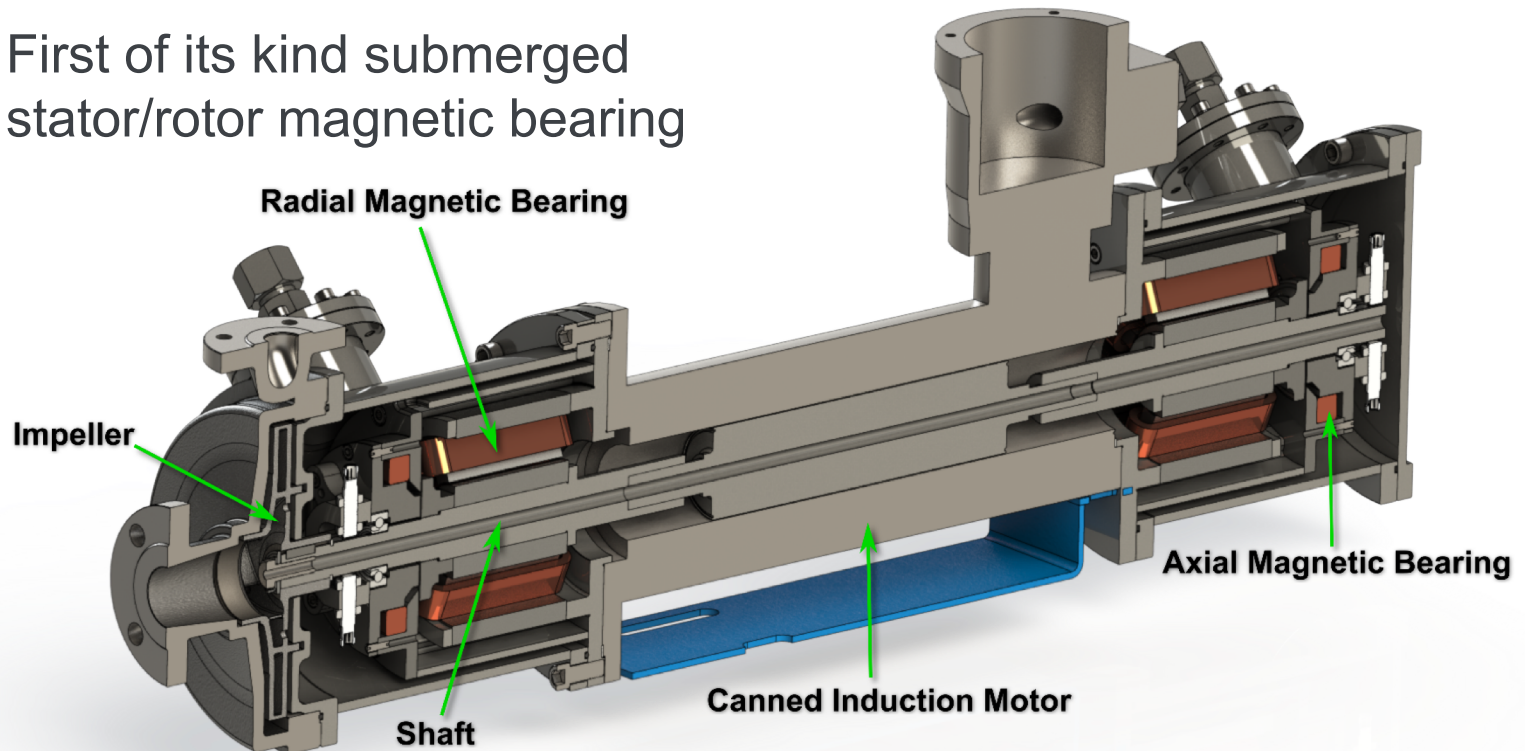
Project Overview

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



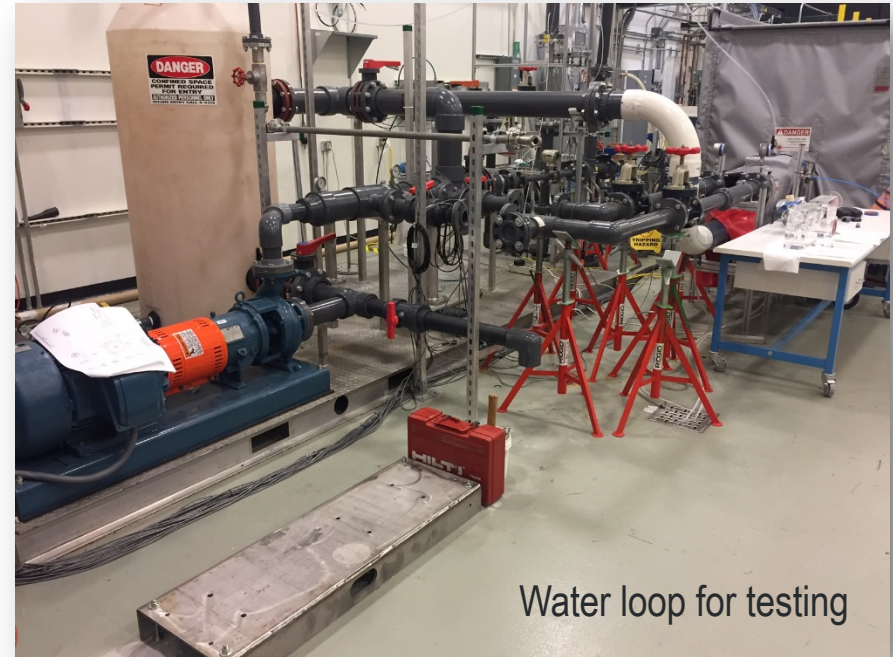
Project Overview

- 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.

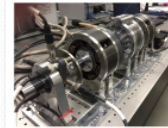
Embedded Instrumentation and Control for Extreme Environments

Dr. Alex Melin, Roger Kisner, F. Kyle Reed, et al.

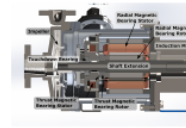
Motivation

- Demonstrate how cross-cutting embedded I&C techniques (beyond PLC and PID) can improve performance and enable new component designs
- Develop two magnetic bearing testbeds to test embedded I&C for extreme environments (with the eventual goal of a 700 °C molten salt pump)
- Develop design methods for creating high-performance, reliable components for extreme environments
- Utilize a physic-based design strategy and embedded controls for coupled system design to take advantage of subsystem interactions

Testbed Designs¹⁻¹⁰

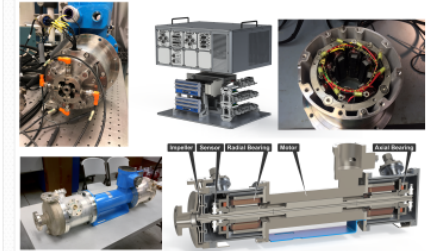


Bench-Scale Testbed
 • 500 N Force (112 lbf)
 • 10 μm shaft positioning accuracy
 • 0-30 A bearing current



Submerged Testbed
 • 2000 N Force (450 lbf)
 • 10 μm shaft positioning accuracy
 • 0-30 A bearing current
 • 530 L/min, 78 m head
 • 3600 RPM

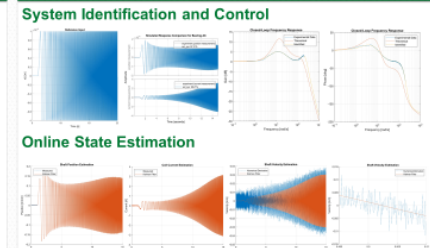
Testbed Assembly^{2,3,4,5}



Embedded I&C^{2,4,5,6,7}

- System identification
 - Linear model identification
 - Nonlinear grey-box parameter estimation
- Linear Quadratic Gaussian Controller
 - Multi-input/multi-output controller to minimize gyroscopic and fluid force disturbances on shaft vibration
- Unscented Kalman Filter
 - Online state estimation
 - Integrated sensing of disturbance forces

Selected Results²



References:

- [1] Melin, A. M., Kisner, R. A., "Design and Analysis of Embedded I&C for a Fully Submerged Magnetically Suspended Impeller Pump," Nuclear Technology, vol. 123, 2018.
- [2] Melin, A. M., Kisner, R. A., "Embedded Sensors and Controls to Improve Component Performance and Reliability – Final Report," ORNL Report, ORNL/TM-2018/811, 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., "Embedded Sensors and Controls to Improve Component Performance and Reliability – Bench-Scale Testbed Design Report," ORNL Report, ORNL/TM-2018/906, October 2018.
- [5] Melin, A. M., Dirka, A., et al., "Embedded Sensors and Controls to Improve Component Performance and Reliability – Bench-Scale Testbed Design Report," ORNL Report, ORNL/TM-2015/984, 2015.
- [6] 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.
- [7] 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-2015/415, September 2015.
- [8] Melin, A., et al., invited Paper: "Advanced Instrumentation for Extreme Environments," IEEE Instrumentation and Measurement Magazine, 2015.
- [9] Kisner, R. A., Fugate, D. L., Melin, A. M., Holcomb, D., Wilson, D., Silva, P., and Cruz-Molina, C., "Evaluation of Temperature-Dependent Manufacturing of Embedded Sensors and Controls with Canned Rotor Pump System," ORNL Report, ORNL/TM-2015/269, July 2015.
- [10] 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.

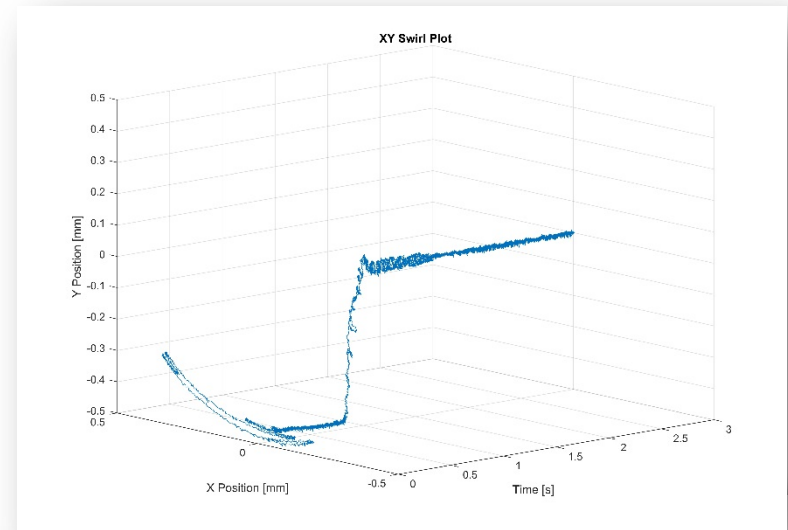
Accomplishments

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



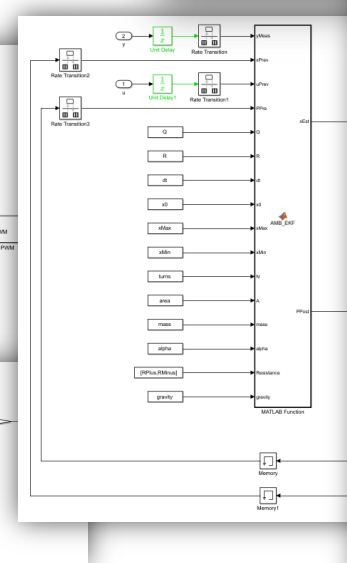
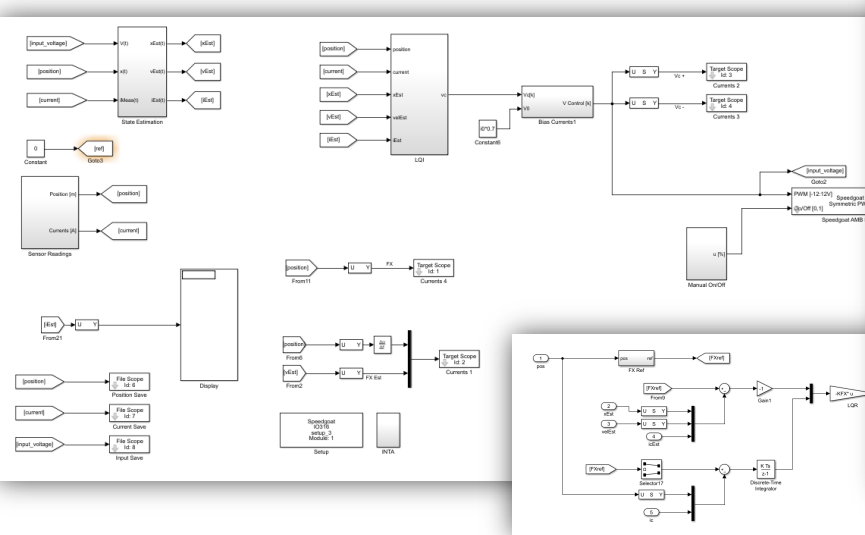
Accomplishments

- 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



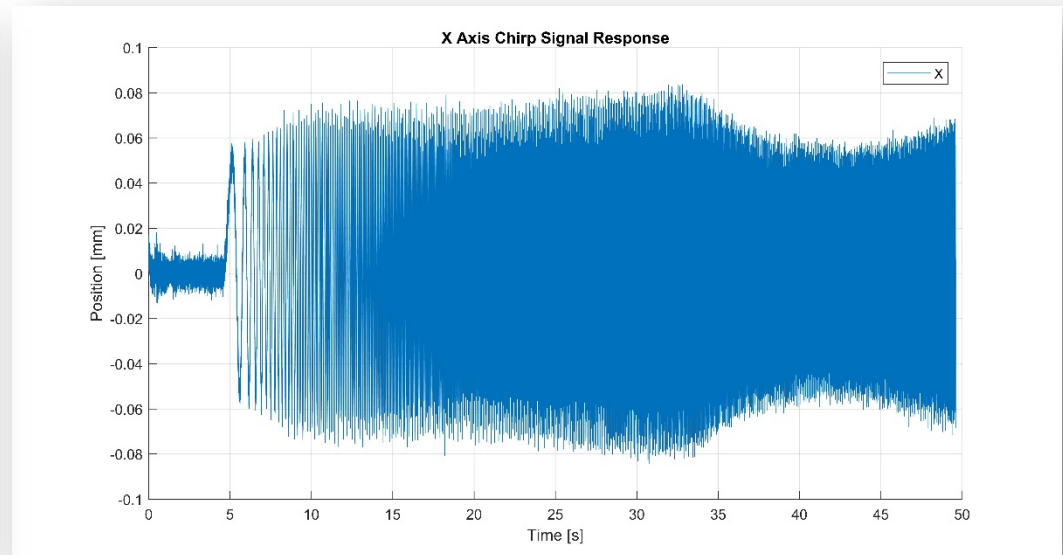
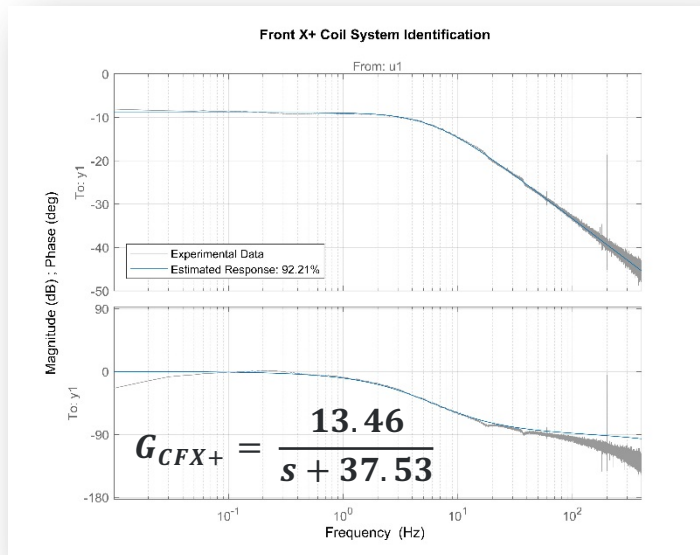
```
absEst(1,1) = absEst(1,1) + dt * (-absEst(3)/(k0*absEst(1,1))*k2rev(2) - (2*Resistance(1)/k0)*k2rev(1) + (2*(k0*absEst(1,1)/k2)*k2rev(1) + kMax(4,1) - absEst(4) - dt * (-k2rev(4)/(k0*absEst(1,1))*k2rev(2) - (2*Resistance(2)/k0)*k2rev(4) + (2*(k0*absEst(1,1)/k2)*k2rev(2) ));
```

```
% Limit the shaft motion after updating  
if 2*sgt(R(1,1)) >= abs(xMax - absEst(1))  
    if absEst(1,1) > 0  
        absEst(1,1) = xMax;  
    else  
        absEst(1,1) = -xMax;  
    end  
end  
if abs(absEst(1) - xMin) <= 2*sgt(R(1,1))  
    if absEst(1,1) < 0  
        absEst(1,1) = xMin;  
    end  
end  
% Calculate the system Jacobian matrix by linearizing about the  
% current point.  
F11 = 1;  
F12 = dt; %  
F13 = 0;  
F14 = 0;  
F21 = dt*( (2*k/Mass)*(k2rev(3))^2*(k0*absEst(1))^3 ) + (2*k/Mass)*(k2rev(4))^2*(k0*absEst(1))^3);  
F22 = 1;  
F23 = dt*( (2*k/Mass)*k2rev(3)/(k0*absEst(1))^2 );  
F24 = -dt*( (2*k/Mass)*k2rev(4)/(k0*absEst(1))^2 );  
F31 = dt*( -k2rev(3)/(k0*absEst(1))^2)*k2rev(2) + (2*Resistance(1)/k2)*k2rev(3) - (2/k2)*k2rev(1) );  
F32 = -dt*(k2rev(3)/(k0*absEst(1)));  
F33 = 1 + dt*( -1/(k0*absEst(1))^2)*k2rev(2) - (2*Resistance(1)/k2)*(k0*absEst(1) );  
F34 = 0;  
F41 = dt*( -k2rev(4)/(k0*absEst(1))^2)*k2rev(2) - (2*Resistance(2)/k2)*k2rev(4) + (2/k2)*k2rev(2) );  
F42 = dt*(k2rev(4)/(k0*absEst(1)));  
F43 = 0;  
F44 = 1 + dt*( 1/(k0*absEst(1))^2)*k2rev(2) - (2*Resistance(2)/k2)*(k0*absEst(1) );  
F = [F11, F12, F13, F14; ...  
     F21, F22, F23, F24; ...  
     F31, F32, F33, F34; ...  
     F41, F42, F43, F44];  
% Prediction Step  
absEst = absEst;  
FFcov = FFcov*F' + Q;  
% Update Step  
JK = FFcov - FFcov*F'*R*F*FFcov;  
sk = FFcov*F'*R; %  
sk = FFcov*F'*R;  
% Calculate the estimate and posterior covariance  
absEst = absEst + sk*Y;  
FFcov = (eye(4) - sk*R'*R*sk)*FFcov;
```



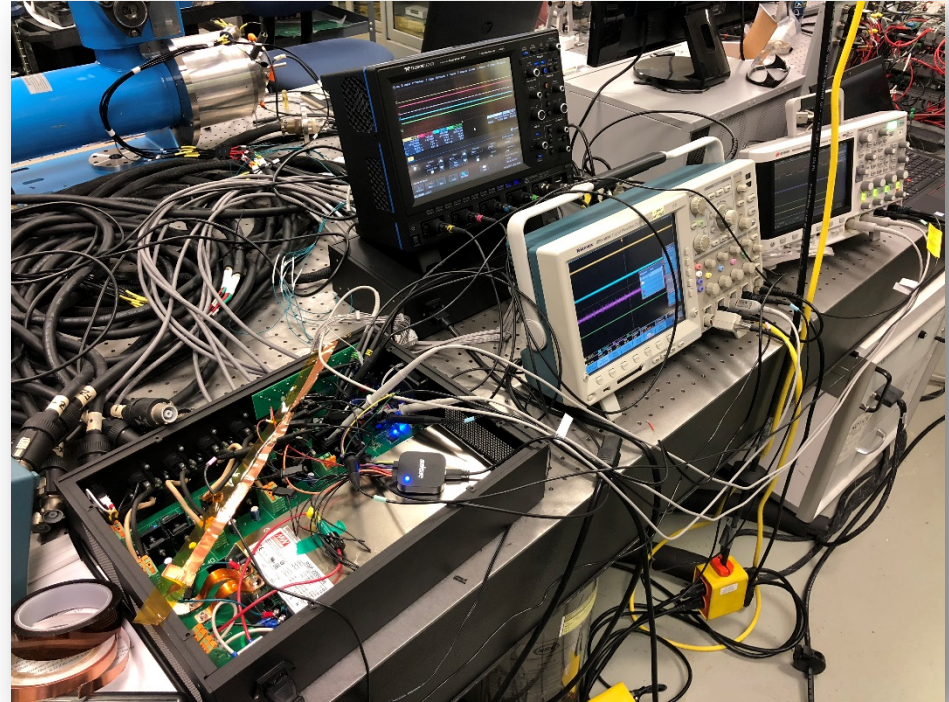
Accomplishments

- 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.



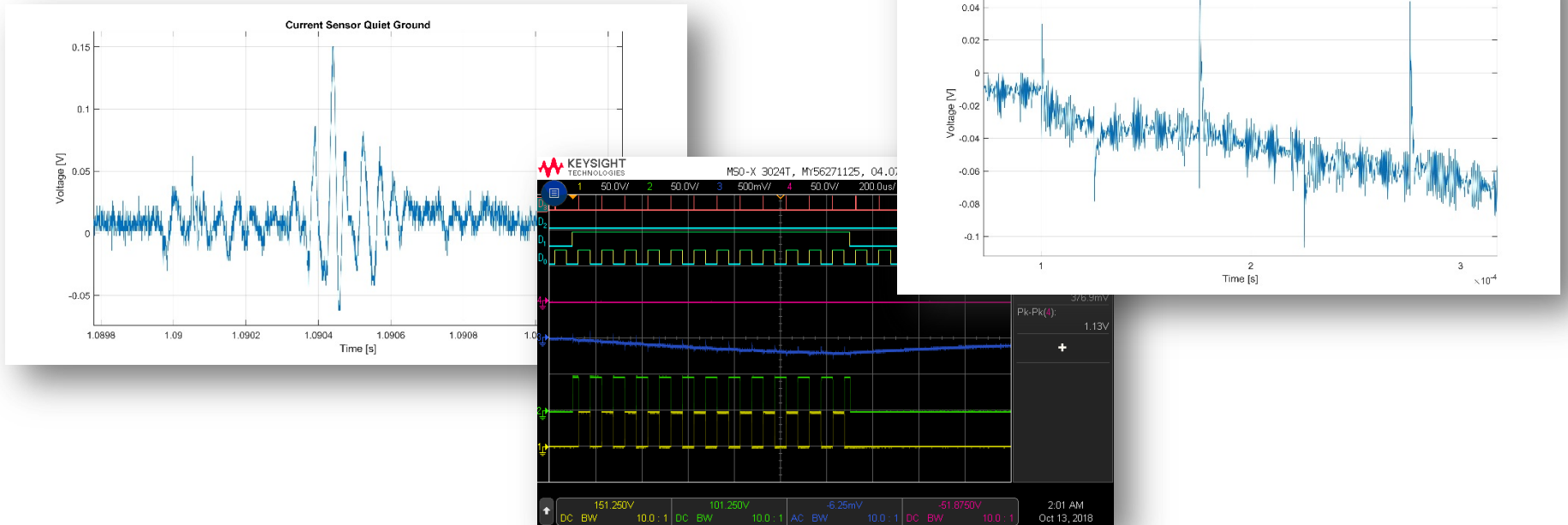
Accomplishments

- 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.



Clean. **Reliable. Nuclear.**

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