Fiber Sensor Fused Additive Manufacturing for Smart Component Fabrication for Nuclear Energy

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Project Objectives

• Development Digital Twin of AM process supported by sensor measurements.
• Optimization of AM processing to embed distributed fiber sensors.
  – Direct Metal Laser Sintering
  – Laser Energized Net Shaping
  – Powder Binding and Sintering process
  – Ultrasonic Process
• New optical fibers with high TEC for sensor-fused smart components
  – New materials for NE (Zr, Invar, Inconel, SS)
  – Material properties (high T, corrosion, radiation resilience)
• Demonstration of multi-parameter measuring in radiation environments
Technical Progress/Accomplishments

Why is this important?

Development of radiation harden distributed and multiplexable sensors for NE

- Femtosecond laser reel-to-reel sensor fabrications
- Interrogation systems readily to be integrated with I&C
- Computationally efficient sensor demodulation algorithm
- High-resolution sensor data enabled artificial intelligence
- Improve overall TRL for fiber sensor for near-future deployment
Fiber Sensor Fabrication

**Reel-to-reel oil-immersion fiber writing setup**

- Fast and continuous fabrication over >tens meters
- -fs (190fs – 5 ps), 800-nm, 532-nm, 355 nm outputs
- Sensors fabrication over 20 m continuously
- Applied to wide array of rad-hard fibers
- Real-time monitoring
- New laser system comes online
Sensor Fabrications

Fs-laser inscription of Type-II Nanograting and IFPI Sensor Array

FBG Sensor String

Laser Enhanced Rayleigh Scattering Profile
Optimization of Sensor Fabrications: IFPI arrays

Optimization of Laser Processing to Ensure High-T Stability and Low-Loss

- Nanograting formation threshold at 100 nJ pulse energy
- With the increase of pulse energy, size of nanograting increases
- High visibility of 0.49 at optimized pulse energy of 160 nJ
- Low insertion loss of 0.0024 dB per sensor
Rapid Demodulation Algorithm and Interrogation Systems for NE I&C

- Phase based demodulation
- Robust algorithm avoid “phase jump”
- Computationally efficient
- Easy implementation into DSP chips
- Dedicate sensor demodulation electronics developed
- Support 2 kHz sampling rates
- 40-nC or 0.01C temperature accuracy.
- Eight channels to support >200 sensor simultaneously

Bunman Frequency Estimation

\[
F(\xi) = \sum_{n=0}^{N-1} \gamma e^{i(\frac{l\Delta kn + l\theta_n + \phi_0}{N})} e^{-2\pi i \xi/N}
\]

\[
= \gamma e^{-l\theta_0 + \phi_0 + \pi\left(\frac{l\Delta k}{2\pi} \xi \cdot \frac{N-1}{N}\right)} \sin[\pi\left(\frac{l\Delta k}{2\pi} \xi - \xi\right)] \sin[\pi\left(\frac{l\Delta k}{2\pi} - \xi\right) / N]
\]

\[
\phi(\frac{l\Delta k}{2\pi}) = \phi_m + 2\pi a = \frac{\varphi_m}{2\pi}
\]

\[
\xi_p = \frac{k_1 - k_2}{k_0} \left(\phi_m - \phi_0 + 2\pi [a]\right)
\]
Sensor Data Enabled Artificial Intelligence

FBG Sensor In-Pile Testing

- Machine learning mitigation of sensor drifts
- Bayesian learner for reactor anomaly event detection
- 98.3% of sensor drift can be eliminated through ML
- Anomaly event detected if event-induced 3°C temperature variation can be detected.
- “Bad Sensor” is better than No Sensor!
First High Spatial Resolution Temperature Profile Measurements of a Reactor Core

- Laser Enhanced Fibers
- Pristine Fiber

- In-pile measurements at (560°C, $1.4 \times 10^{14}$ f n/s/cm²)
- 1.6-m core profile, 3-cm resolution, 1-s update rate.
- Femtosecond laser fabrication critical
- High resolution data useful for VR and Digital Twin
Improving TRL for Reactor Deployments

- Comprehensive FBG sensor array high-T testing (900ºC-1000ºC)
- Interrogation electronics and algorithm used for demodulation
- Average STD <0.6ºC over 10 days spans at 900ºC (comparing with TC)
- Further increase sensor counts (200) and testing duration (2 months) in 2021.
Challenge: How to embed these sensors into NE Systems?

– Additive manufacturing: make sensor part of smart component design and fabrications from get-go!
– Can sensors survive extreme AM process?
– What is the best AM fabrication strategy?
– Can sensor be embedded in components with complex shape?
– Can we ensure quality of sensor-fused smart components (corrosion, high-T durability, radiation-resilience…)?
– What kind of measurement functions can we achieve, what are benefits?
Sensor-Fused AM Process

- High resolution real-time T & $\mu\varepsilon$ measurements
- Design proper structures to embed sensors without disturbing AM process and part itself
- Real-time measurements to study AM process itself
- Post-process monitoring to study residual strain formation and relaxation.
- Compare, correct, and validate DT
Temperature Modeling vs. Measurement

\[ \rho C_p \frac{dT(r, t)}{dt} = -\nabla \cdot q(r, t) + Q(r, t), r \in V \]

Dirichlet boundary conditions

\[ T = \bar{T}, \quad r \in S_D^T \]

Neumann boundary conditions:

\[ -k \nabla T \cdot n = q, \quad r \in S_N^T \]

Robin boundary conditions:

\[ -k \nabla T \cdot n = h(T - T_a), r \in S_R^T \]
Strain Modeling vs. Measurements

- Two-layer deposition (red box) as the representative volume of the large deposition area (upper).
- Laser scanning strategy in the laser fusion process (lower) Modeled.
- Measurements performed at 4-mm spatial resolution.
- Simulation consistent with modeling, provide confidence for model-based optimization.
Project Impacts

• Patents
  2. (To be awarded) Kevin Peng Chen, Mohamed A. Bayoumy, Aidong Yan, Rongzhang Chen, “Optical fiber-based sensing for smart electrical cable and distributed radiation detection,” US Patent to be awarded in (2020).

• Involvement
  − Engage with both national labs and industry to explore commercialization pathway.
Milestones and Deliverables for FY-20

• Development of simulation framework and code to perform temperature and stress profile for both sensor fused LENS and DMLS AM processes.

• Development of comprehensive sensing scheme to monitor AM process
  − Embedded fiber sensors
  − Optical monitoring

• Develop new sensor fabrication technique using femtosecond laser
  − Establish reel-to-reel continuous fabrication
  − Validate sensor performance based on radiation-harden fibers
Issues and Concerns

- COVID-19 Limits Lab Access and Travel
- No yet to receive account number from the University (due to COVID?)
Milestones and Deliverables for FY-21

- Development of simulation framework and code to perform temperature and stress profile for both sensor fused LENS and DMLS AM processes.

- Develop new specialty optical fibers and innovative fiber metal coating
  - Collaboration with Corning to develop germanosilica based fiber (both core and cladding to achieve TEC 5ppm, silica fiber TEC 0.5ppm)
  - New metal/ceramic coating scheme (heat laser pedestal approach, cold spray, plating)
  - Embedding in relevant metal materials
    - Inconel
    - Zr
    - Invar
Possible Areas/Industries/Programs (and Readiness) for Adoption

Turn-key solutions of fiber sensor being developed that is affordable and customizable for NE.

- Sensor TRL-6 and going up
- Sensor embedding process: TRL-2 aiming to TRL-6 (Thank you for this NEET project!)

• Idaho National Lab: SMR and micro-reactors
• ORNL
• Industry

Cross-cutting nature!

• Solid Oxide Fuel Cell
• Natural gas pipelines
• Naval applications
Contact Information and Questions

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Collaboration Welcome!