Fully Distributed Acoustic and Magnetic Field Monitoring via a Single Fiber Line for Optimized Production of Unconventional Resource Plays

DE-FE0031786

Daniel Homa

Virginia Tech

U.S. Department of Energy
National Energy Technology Laboratory
2021 Carbon Management and Oil and Gas Research Project Review Meeting
August 2021
Presentation Outline

- Research Approach
- Multi-Material Sensing Optical Fiber
  - Performance Modeling via Theoretical Analyses
  - Fiber Design and Fabrication
- Distributed Acoustic Sensing System
  - Sentek Instrument
- Testing Facilities
- Data Analysis and Visualization
Research Approach

picoDAS™ Fiber Optic Sensing Technology

• Relies on an elegant marriage between a special type of FBG device and a time-division-multiplexing (TDM) signal processing scheme

• Superior performance
  – 100 times more sensitive than traditional DAS systems
  – Uniform sensitivity distribution across entire sensing range
  – Capable of multi-parameter measurements.
Research Approach

Multi-Material Magnetic Sensing Fiber

- Single mode optical fiber core with a magnetostrictive material in the cladding
  - The magnetostrictive material expands or contracts upon exposure to a magnetic field, inducing a strain on the FBG based interferometers in the optical fiber
  - Stack-and-draw technique utilized to incorporate dissimilar materials in the fiber via optical fiber draw
- Magnetostrictive materials
  - Terfenol-D™, Metglas 2605®, Nickel
- All other sensing schemes require bonding of the magnetostrictive material to the fiber, including it in the coating, and/or utilizing other post-processing schemes
Research Approach

Demonstration of Magnetic Sensing System

• Response of a prototype sensing fiber to a magnetic field generated by the alternating current of an air solenoid
  – Minimum Magnetic Field: ~0.2 mT
• Performance improvements
  – Increase relative diameter of magnetostrictive wire
  – Enhance coupling efficiency
  – Use of materials that exhibit larger magnetostriction (Metglas®)
• Improve fiber handling and splicing techniques
Technical Status

Theoretical Modeling

• Developed theoretical models and techniques to optimize magnetic sensing fiber performance and evaluate response to magnetic field
  – Met Success Criteria for Milestone 2: Minimum Sensitivity of 10 mT
Technical Status

Laboratory Scale Test Facilities

- Test stands (2) to evaluate magnetic response of sensing fiber
  - Air-core solenoid
  - Length = 2 meters, 5 meters
- Soil test beds (2) for simulated environmental testing
  - Uniform earth material
  - Controlled magnetic and acoustic sources
  - Bare sensing fiber/Cemented in metal tubing
- High temperature testing (>150°C)
- Met Success Criteria
  - Minimum Magnetic Field Exposure: 1mT
  - Maximum Exposure Temperature: ≥ 150°C
Technical Status

Multi-Material Sensing Fiber Fabrication

• Developed improved techniques to fabricate relatively long lengths (>500 m) of uniform multi-material sensing fibers samples
  – Magnetostrictive cladding wires: Ni, Metglas®
  – Multiple number of magnetostrictive rods: 2/3
  – Acrylate coating

• On Schedule to meet Success Criteria
  – Fiber Length: >50 m
  – Tensile Strength of >50 kpsi

• Successfully inscribed FBG based sensors via femtosecond laser inscription
Technical Status

picoDAS System Development

• Systematically tested and evaluated Sentek DAS systems
  – Demonstrated measurement resolution of 0.2 nanostrain as defined by $3\sigma$
  – Demonstrated spatial resolutions of 2 m and 5 m
• Reduced interrogator size (6U to 4U) to permit the use of an instrument enclosure with a height reduced from 6U to 4U
• On Schedule/Met Success Criteria
Technical Status

System Demonstration and Data Analysis

- Evaluated picoDAS system using buried sensing cable
- Developed data analysis software suite

Car Driving

Hammer Drop/Tamper

Shovel Digging
Technical Status

Fast ICA Algorithm Development

- Separation of mixed acoustic and magnetic responses in real time
  - Provide enhanced value to geoscientists; We are testing and improving upon the fast independent component analysis (ICA) method to separate mixed signals
- Demonstrated the fast ICA algorithm to separate mixed signals

Observed mixed signals 80 Hz + 200 Hz

ICA-separated signals

Algorithmically separated matches ideal separation
Accomplishments to Date

• Developed theoretical models and techniques to optimize magnetic sensing fiber performance and evaluate response to magnetic field
• Designed, constructed and commissioned laboratory test facilities to evaluate the sensor response to acoustic and magnetic fields
• Successfully fabricated continuous (> 500 m) multi-material sensing fibers with Ni and Metglas cladding wires
• Fabricated FBG based sensors in multi-material fibers via femtosecond laser inscription
• Successfully designed and manufactured picoDAS interrogators with 2 and 5 meter spatial resolution
• Systematically tested the Sentek DAS systems to demonstrate a measurement resolution of 0.2 nanostrain as defined by 3σ
• Evaluated the performance of the picoDAS system with a buried sensing cable upon exposure to varied acoustic stimuli
• Completed initial full sensing system integration
Lessons Learned

– Fabrication of long lengths (~kms) of uniform multi-parameter sensing fiber required significant process development
  • Optimized preform stacking design and assembly techniques
  • Optimized draw parameters (preform feed rate/draw speed)
– Optical coupling from standard single mode fiber to the multi-material sensing fiber remains a challenge
  • Investigated methods for fiber termination
  • Developed splicing parameters to ensure adequate optical coupling
– Optimization of magnetostrictive wire sizes and spacing in cladding was necessary to inscribe high quality FBGs
Synergy Opportunities

• High resolution sensing and imaging of the subsurface will provide operators with more clarity of the subsurface and the real-time information for optimized drilling and production.
  – Cross-well Imaging Techniques
  – Passive/Active Magnetic Ranging
  – Position Monitoring for Downhole Completion Devices
  – Monitoring while Drilling (MWD)/Logging while Drilling (LWD)
  – Permanent Well Monitoring

• Reliability and performance capabilities of the fiber optic sensing system will assure that the operators have the most reliable and accurate information necessary to make critical decisions.
Project Summary

– Key Finding

• Theoretical modeling demonstrated adequate sensitivity (<1 mT) can be achieved with multi-material sensing design
• Successfully demonstrate the ability to fabricate long (>500 meters) continuous lengths of multi-material sensing fiber
• Demonstrated superior performance of prototype picoDAS systems
• Developed the basis for the ICA analysis techniques for single separation

– Next Steps

• Optimize ICA algorithms to enhance signal separation
• Manufacture and test “rackable” 4U picoDAS interrogator
• Fabricate long lengths (>1 km) multi-material (Ni, Metglas®) sensing fiber
• Perform full system integration and testing
• Optimize sensing fiber design for optimal performance
• Begin initial planning for field trial deployment
Acknowledgements

Department of Energy
National Energy Technology Laboratory
Project Manager: Gary L. Covatch

Prysmian Group
Industrial Support: Brian Risch, Ph.D.

Halliburton
Industrial Support: Dorothy Wang, Ph.D.

Prysmian Group
Linking the Future

Weatherford
Industrial Support: Zhuang Wang, Ph.D.
THANK YOU FOR YOUR TIME

Questions?
Appendix

– Benefit to the Program
– Project Overview
– Organization Chart
– Gantt Chart
– Bibliography
Benefit to the Program

• The technologies developed in this program will have an immediate and profound impact on the widespread approach to both subsurface imaging and distributed fiber optic sensing
  – Distributed multi-parameter sensing on a single fiber will provide operators with a tool with unprecedented sensing density

• Provide operators with an enhanced electromagnetic field mapping tool
  – Enable improved resolution imaging of the subsurface and potentially aid in the discovery of new subsurface phenomena

• Provide operators with the most reliable and accurate information necessary to make the critical decisions to ensure the best use of the Nation’s subsurface resources
Project Overview
Goals and Objectives

• **Objective**: Develop a fiber-optic sensing system capable of real-time simultaneous and distributed measurements of multiple subsurface parameters via a first-of-its-kind optical fiber with an electromagnetic field sensing capability over an unprecedented sensing length

• **Goal**: Design and fabricate a multi-material sensing fiber for distributed magnetic field and acoustic measurements

• **Goal**: Design and construct an optical interrogation system and develop the sensing algorithms for distributed magnetic field and acoustic measurements with ultra-high sensitivity via a single sensing fiber

• **Goal**: Demonstrate the performance of a fully integrated multi-parameter sensing system in a simulated laboratory environment
# Project Overview

## Success Criteria

<table>
<thead>
<tr>
<th>ID</th>
<th>Title</th>
<th>Description</th>
<th>Result</th>
<th>Decision Point</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC1</td>
<td>Theoretical Evaluation</td>
<td>1. Minimum Sensitivity: 10 millitesla (mT)</td>
<td>&lt;10 mT</td>
<td>D1</td>
<td>9/30/20</td>
</tr>
<tr>
<td>SC2</td>
<td>Test Facilities</td>
<td>1. Maximum Exposure Temperature: ≥ 150°C</td>
<td>&gt;150°C</td>
<td>D1</td>
<td>9/30/20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Minimum Magnetic Field Exposure: 1mT</td>
<td>&lt;=1 mT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC3</td>
<td>Fabrication of Magnetic Sensing Fiber</td>
<td>1. Minimum Fiber Length: 50 m</td>
<td></td>
<td>D2</td>
<td>9/30/21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Minimum Tensile Strength of 50 kpsi</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC4</td>
<td>Distributed Acoustic and Strain Sensing System</td>
<td>1. Minimum Spatial Resolution: 2m</td>
<td></td>
<td>D2</td>
<td>9/30/21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Minimum Strain Sensitivity: 0.5 nanostrain</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC5</td>
<td>Distributed Magnetic Sensing System</td>
<td>1. Sensing Length: &gt; 1 km</td>
<td></td>
<td>--</td>
<td>9/30/22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Minimum Spatial Resolution: 5m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Minimum Magnetic Field Sensitivity: 2 mT</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Organization Chart

- **Lead PI**: Dr. Gary Pickrell (Virginia Tech, CPT)
  - Provide executive management for all phases of the project, and oversee the selection, fabrication, and characterization of the fibers.

- **Co-PI**: Dr. Eileen Martin (Virginia Tech)
  - Support all phases of the project and provide expertise in all technical aspects of the project and efforts pertaining to the testing and analysis of the selected optical fibers.

- **Co-PI**: Dyon Buitenkamp (Sentek Instrument)
  - Daily project management, to include technical insights, under the guidance of the PI and Co-PI.

- **Technical Manager**: Dr. Daniel Homa (Virginia Tech)
  - Daily project management, to include technical insights, under the guidance of the PI and Co-PIs
### Gantt Chart

<table>
<thead>
<tr>
<th>Task #</th>
<th>Task Name</th>
<th>Project Year 1</th>
<th>Project Year 2</th>
<th>Project Year 3</th>
<th>PY 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Project Management and Planning</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>MILESTONE 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Workforce Readiness Plan</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Data Management Plan</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Technology Maturation Plan</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Theoretical Modeling and Analyses</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>MILESTONE 2 / DECISION POINT 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Construction of the Simulated Subsurface Test Facilities</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>MILESTONE 3 / DECISION POINT 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Multi-Parameter Sensing Fiber</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.1</td>
<td>Preform and Fiber Fabrication</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.2</td>
<td>Fiber Grating Array Fabrication</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>MILESTONE 4 / DECISION POINT 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Demonstration of Distributed Sensing System</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.1</td>
<td>Interrogation Design and implementation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.2</td>
<td>Distributed Sensing System Construction and Demonstration with Commercial Fibers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>MILESTONE 5 / DECISION POINT 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Fabrication of High Temperature DAS Fiber</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Integration of Distributed Sensing Fiber and System</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.1</td>
<td>Fabrication of Distributed Magnetic Sensing Fiber</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.2</td>
<td>Development of the Simulated Subsurface Test Facilities</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.3</td>
<td>Demonstrate Distributed Sensing with Magnetic Sensing Fiber</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.4</td>
<td>Perform Sensor Calibration and Verification</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Prototype Sensing System Testing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.1</td>
<td>Fabrication of Prototype Distributed Magnetic Sensing Fiber</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.2</td>
<td>Construct Multi-Parameter Sensing System</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.3</td>
<td>Test Sensing System and Evaluate Performance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>MILESTONE 6</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Prepare and Submit Final Report</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>MILESTONE 7</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
• Presentation entitled “Development of Joint Acoustic and Magnetic Sensing in a Single Fiber” was accepted to Society of Exploration Geophysicists Annual Meeting workshop on distributed fiber optic sensing on October 1, 2021

• Future Publications
  – Several manuscript submissions planned for Y2/Q4, Y3/Q1
  – M.S. thesis by S. Morgan in Mathematics on fiber-optic sensor signal separation anticipated to submit in Spring ’22
  – Ph.D. dissertation by Z. Hileman in Materials Science and Engineering on magnetic and multi-parameter sensing via multi-material optical fiber to submit in Fall ‘21/Spring ‘22