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

DE-FE0031786

Daniel Homa

VirginiaTech Invent the Future

Virginia Tech

CPT Center for Photonics Technology

Sentek Instrument

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

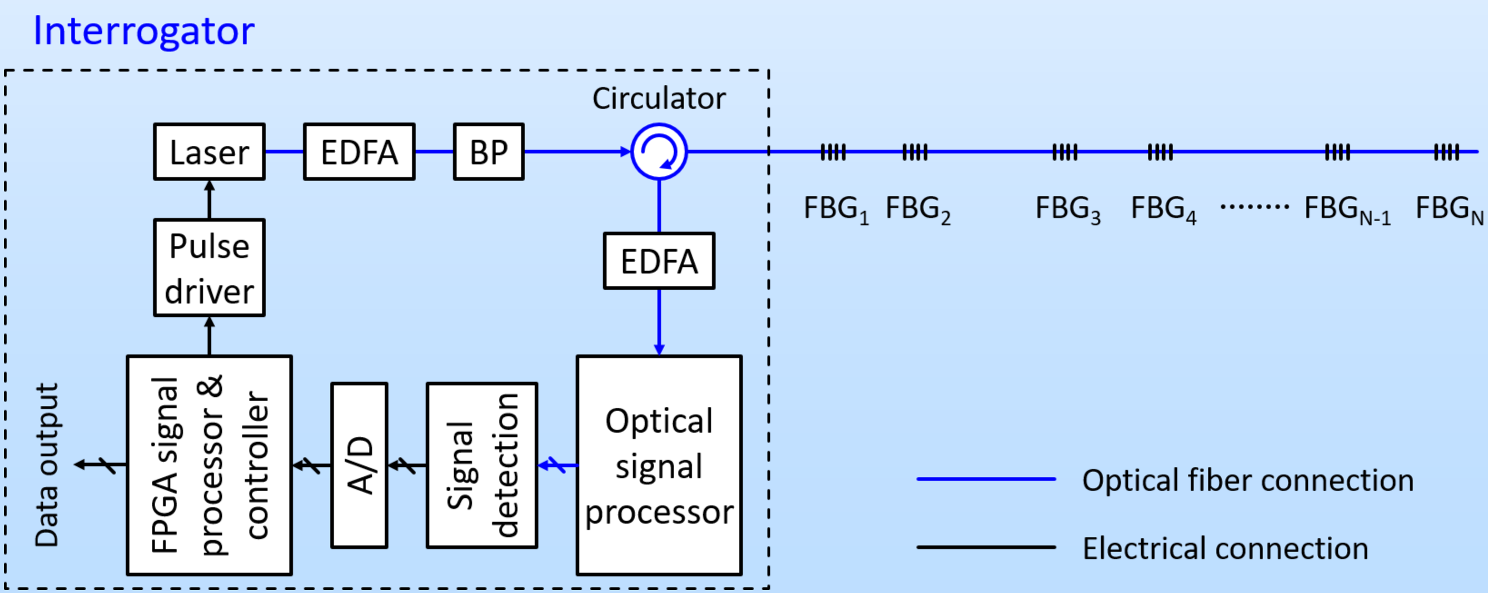
Presentation Outline

- 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

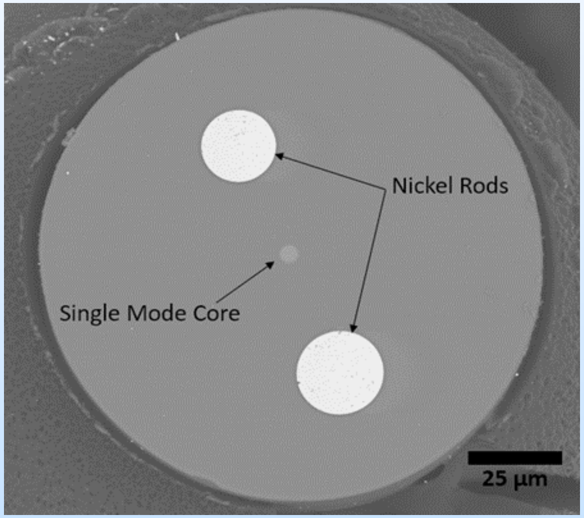
- Relies on an elegant marriage between a special type of FBG device and a time-division-multiplexing (TDM) signal processing scheme
- Superior performance
  - 100 times more sensitive than traditional DAS systems
  - Uniform sensitivity distribution across entire sensing range
  - Capable of multi-parameter measurements.



Research Approach

Multi-Material Magnetic Sensing Fiber

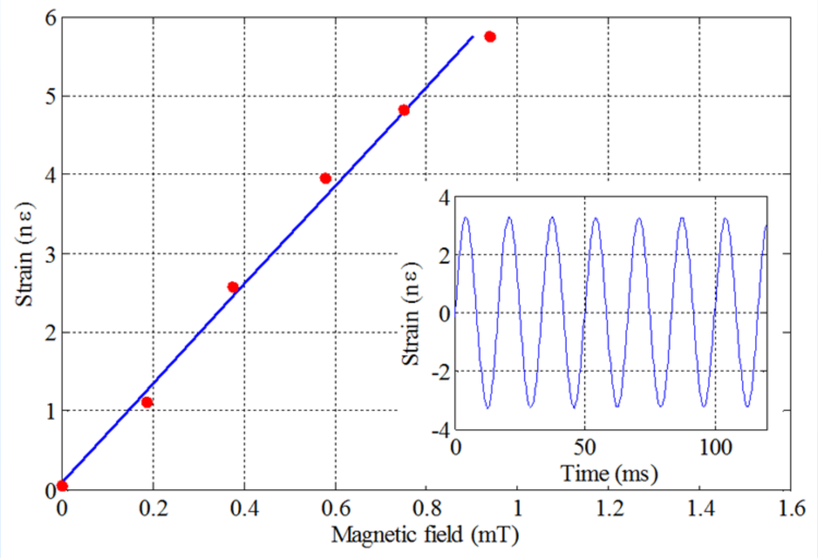
- Single mode optical fiber core with a magnetostrictive material in the cladding
  - The magnetostrictive material expands or contracts upon exposure to a magnetic field, inducing a strain on the FBG based interferometers in the optical fiber
  - Stack-and-draw technique utilized to incorporate dissimilar 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

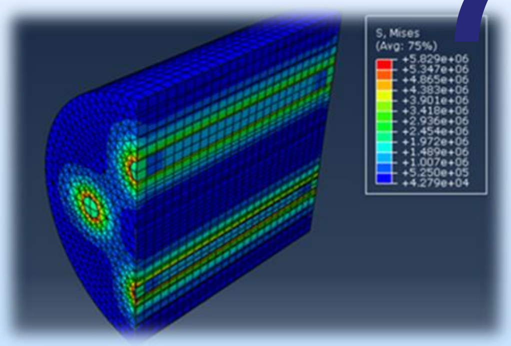
- Response of a prototype sensing fiber to a magnetic field generated by the alternating current of an air solenoid
  - Minimum Magnetic Field: ~0.2 mT
- Performance improvements
  - Increase relative diameter of magnetostrictive wire
  - Enhance coupling efficiency
  - Use of materials that exhibit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

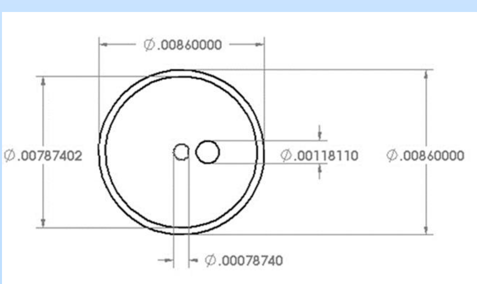


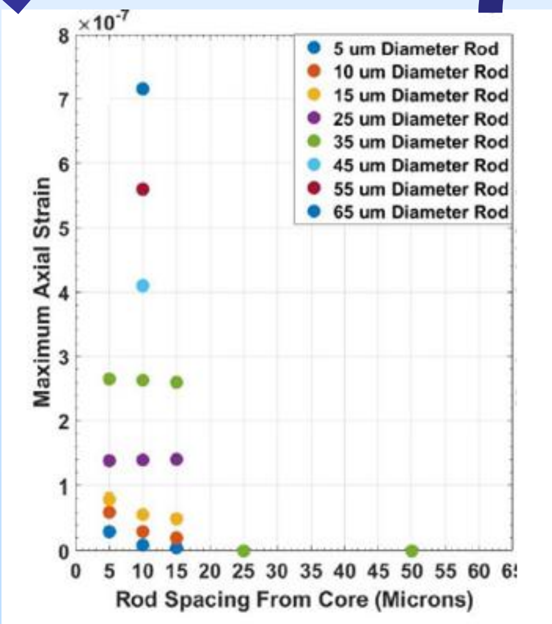
Technical Status

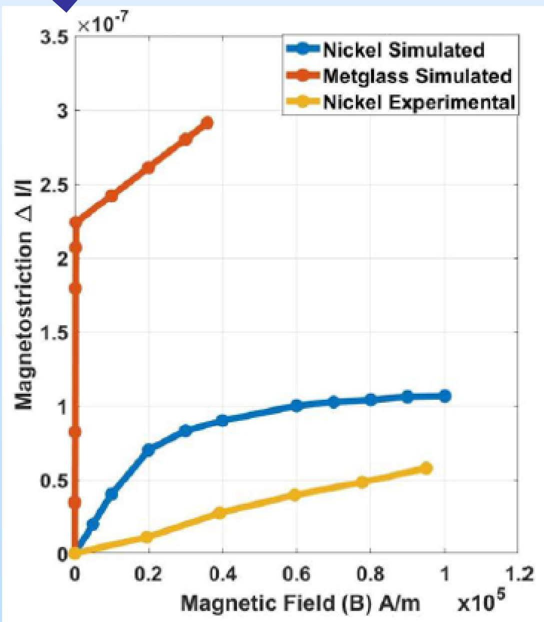
Theoretical Modeling

- 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

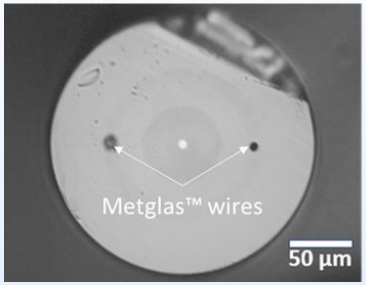
Laboratory Scale Test Facilities

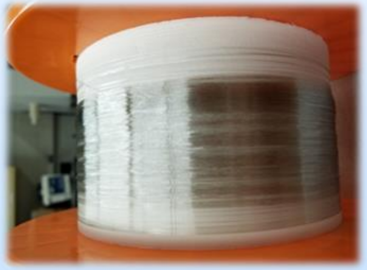
- Test stands (2) to evaluate magnetic response of sensing fiber
  - Air-core solenoid
  - Length = 2 meters, 5 meters
- Soil test beds (2) for simulated environmental testing
  - Uniform earth material
  - Controlled magnetic and acoustic sources
  - Bare sensing fiber/Cemented in metal tubing
- High 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

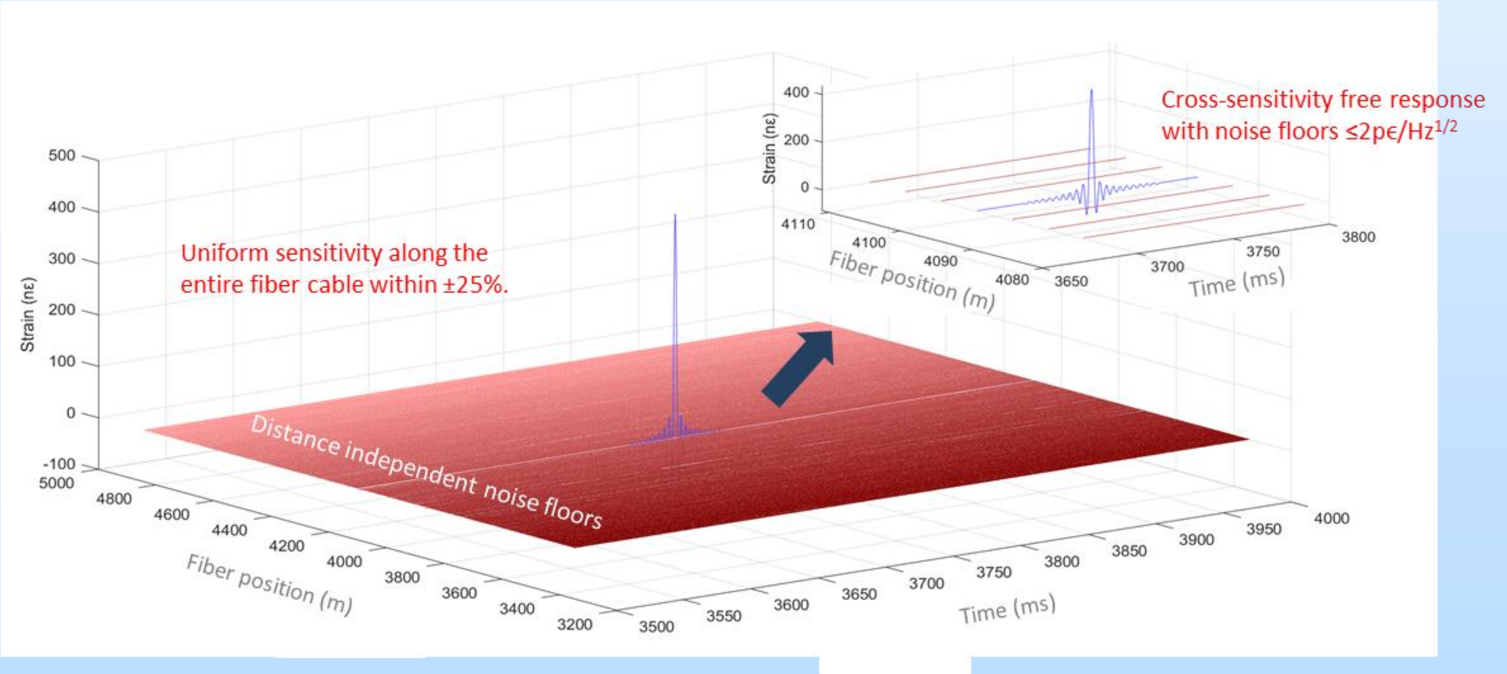




Technical Status

picoDAS System Development

- Systematically tested and evaluated Sentek DAS systems
  - Demonstrated measurement resolution of 0.2 nanostrain as defined by 3σ
  - 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

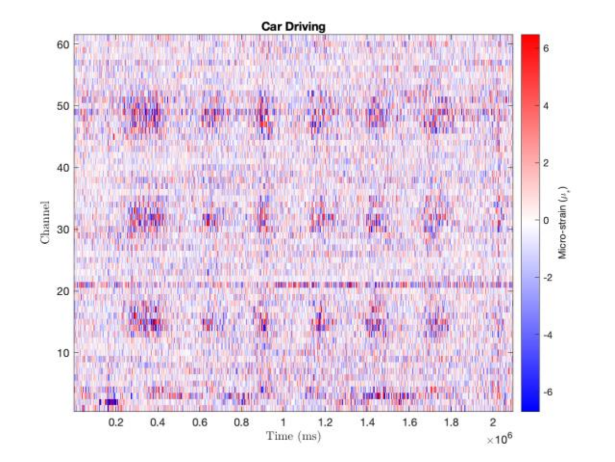


Technical Status

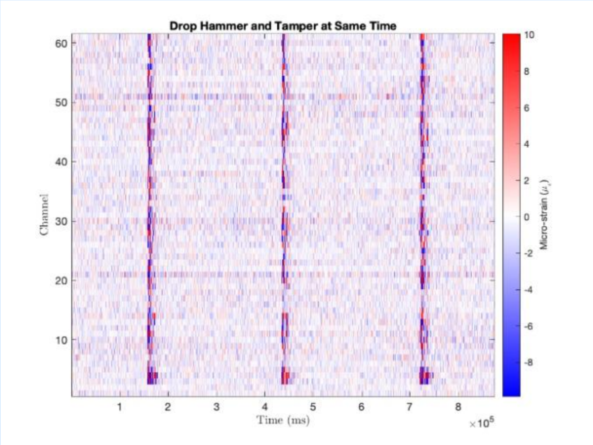
System Demonstration and Data Analysis

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

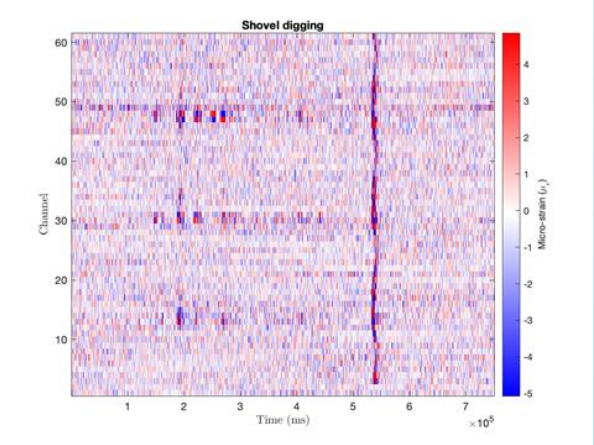
Car Driving



Hammer Drop/Tamper



Shovel Digging

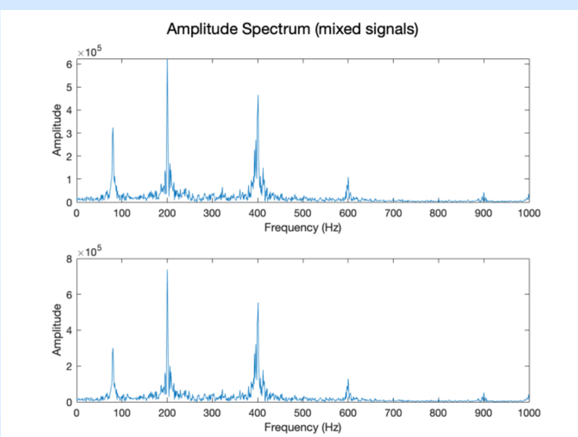


Technical Status

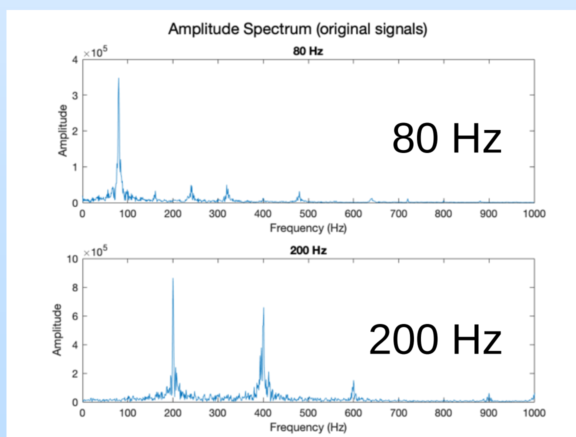
Fast ICA Algorithm Development

- 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

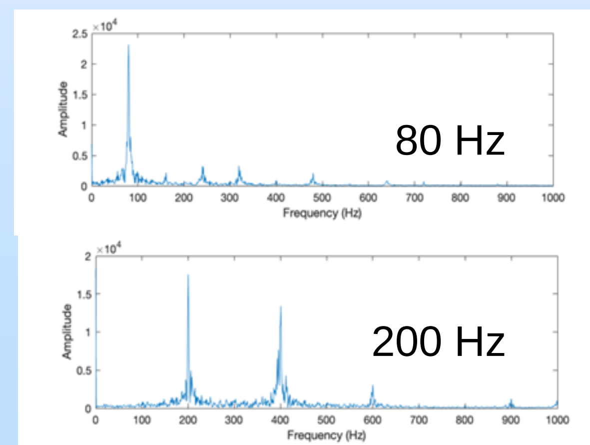
Observed mixed signals 80 Hz + 200 Hz



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 seperation

– 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

Halliburton

Industrial Support: Dorothy Wang, Ph.D.

Prysmian Group

Industrial Support: Brian Risch, Ph.D.

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

- **<u>Objective</u>**: 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
- **<u>Goal</u>**: Design and fabricate a multi-material sensing fiber for distributed magnetic field and acoustic measurements
- **<u>Goal</u>**: 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
- **<u>Goal</u>**: Demonstrate the performance of a fully integrated multi-parameter sensing system in a simulated laboratory environment

Project Overview

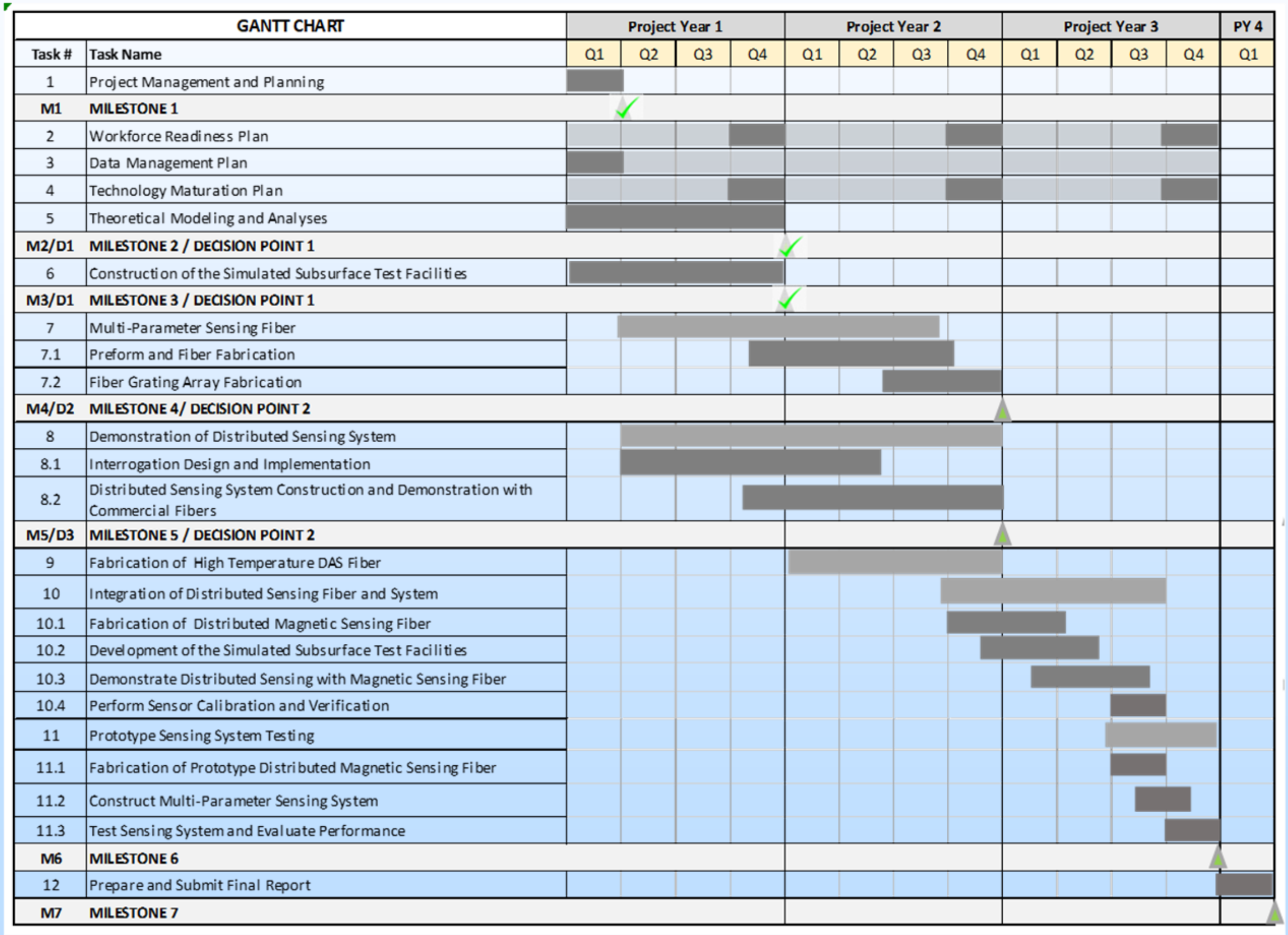
Success Criteria

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

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


GANTT CHART
Project Year 1
Project Year 2
Project Year 3
PY 4
Task #
Task Name
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
Q1
1 Project Management and Planning
M1 MILESTONE 1
2 Workforce Readiness Plan
3 Data Management Plan
4 Technology Maturation Plan
5 Theoretical Modeling and Analyses
M2/D1 MILESTONE 2 / DECISION POINT 1
6 Construction of the Simulated Subsurface Test Facilities
M3/D1 MILESTONE 3 / DECISION POINT 1
7 Multi-Parameter Sensing Fiber
7.1 Preform and Fiber Fabrication
7.2 Fiber Grating Array Fabrication
M4/D2 MILESTONE 4/ DECISION POINT 2
8 Demonstration of Distributed Sensing System
8.1 Interrogation Design and Implementation
8.2 Distributed Sensing System Construction and Demonstration with Commercial Fibers
M5/D3 MILESTONE 5 / DECISION POINT 2
9 Fabrication of High Temperature DAS Fiber
10 Integration of Distributed Sensing Fiber and System
10.1 Fabrication of Distributed Magnetic Sensing Fiber
10.2 Development of the Simulated Subsurface Test Facilities
10.3 Demonstrate Distributed Sensing with Magnetic Sensing Fiber
10.4 Perform Sensor Calibration and Verification
11 Prototype Sensing System Testing
11.1 Fabrication of Prototype Distributed Magnetic Sensing Fiber
11.2 Construct Multi-Parameter Sensing System
11.3 Test Sensing System and Evaluate Performance
M6 MILESTONE 6
12 Prepare and Submit Final Report
M7 MILESTONE 7

Bibliography

- 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