John is a Staff Research Scientist at Luna Innovations where he has worked since 2015. His 20+ years of experience in R&D enables novel applications of fiber optic sensing to aerospace, defense, energy, and other scientific fields. John led a NASA project to develop AI/ML anomaly detection for inflatable space habitat SHM. He currently leads an Army project to develop a silicon PIC for high-speed fiber Bragg grating (FBG) interrogation and also leads a Navy project to develop fiber optic pressure sensors to monitor the health of F-35 hydraulic flight actuators. John received his Ph.D. in Mechanical Engineering from Virginia Tech in 2011.

UPISC UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING

COLLABORATION WORKSHOP

NATIONAL ENERGY TECHNOLOGY LABORATORY

Fiber Optic Sensing for Structural Health Monitoring (SHM)

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LUNA

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Fiber Optic Sensing Technology Overview

Sensing

Sensing Technology

- Scattering Mechanisms
  - Rayleigh
  - Raman
  - Brillouin
- Fiber and Sensors
  - Constellation Fiber
  - FBG Sensors
  - Heat detection fibers

Software Expertise

- Proprietary industry-specific algorithms
- Operator focused interfaces
- SCADA integration
- Robust APIs
- AI/ML

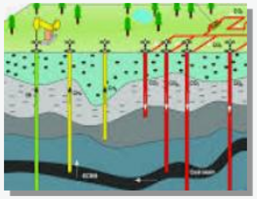
Distributed Acoustic Sensing

Distributed Temperature and Strain Sensing

Point Sensing

High-Definition Distributed Sensing

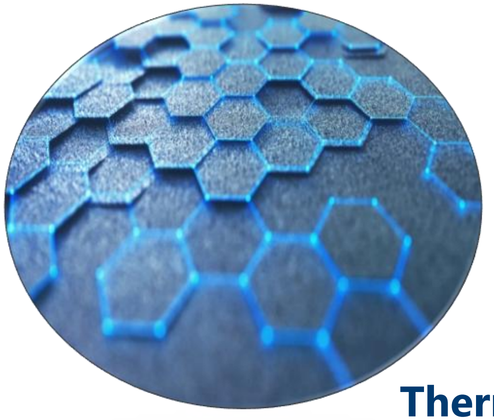
Key Long-Range Sensing Applications

	Midstream	Security (Perimeter & Fire)	Utilities (Cable Monitoring)	Upstream	Scientific (E&I, CCUS)
					
Luna Differentiation	*Algorithms for intrusion and leak detection* *Reliable instruments* *Past performance / references* *Approved vendor status*	*Long range and accuracy with up to 1000 zones* *Fully certified products for fire detection (VDS, FM, UL)* *Track record and MTBF >40 years* *Strong Intrusion detection algorithms*	*Longest range for both instruments* *Proprietary algorithms developed (RTTR, DoB)*	*Constellation Fiber (better signal)* *Instrument with low noise (DAS)* *DTS with very high accuracy and special resolution*	*Complete set of high-resolution instruments* *API to extract the data* *Constellation software*
Key Benefit	*Proven solution which yields accurately categorized alarms while reducing false alarms* *Strong track record of completing major projects*	*Range and track record certificates*	*Total cost of ownership declines as less instruments needed for long range applications* *Cost reduction of deploying a full solution*	*Monitoring solution with proactive recommendations for improved oil recovery* *Cost reduction of deploying a full solution*	*Broadest range of measurements available, eliminates need for multiple purchases* *High-resolution and stable measurement*

High-Definition and High-Speed Sensing Applications

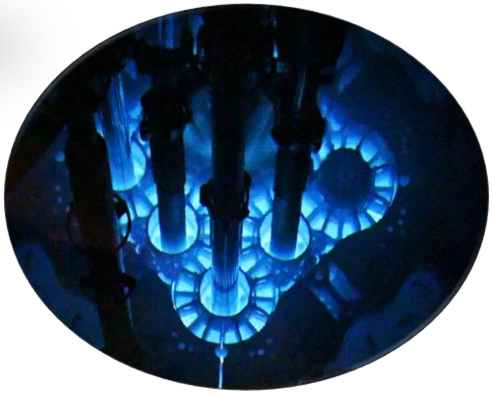
Civil Structures / Infrastructure

Material Science



Electrification

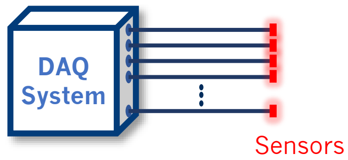
Thermal Characterization

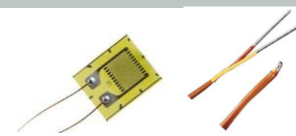


Two Fiber Optic Sensing Methods

Standard, Electrical Approach

Multiple Copper Wires Per Sensor



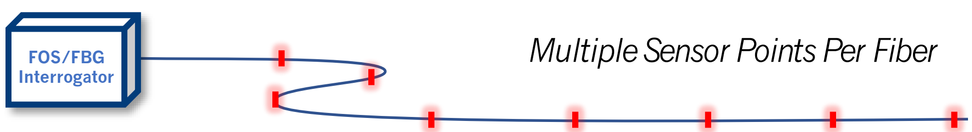


Foil strain gages, thermocouples, RTDs, etc.

- 2-3+ wires per sensor
- Multiple DAQs
- Low resolution
- Bulky, metallic wiring

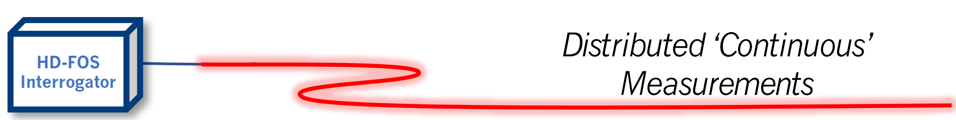
Fiber Optic Sensing

High-Speed Multipoint Sensing



- Single optical fiber
- Static and dynamic measurements
- Long range (km's)
- Easy to install

Distributed Sensing



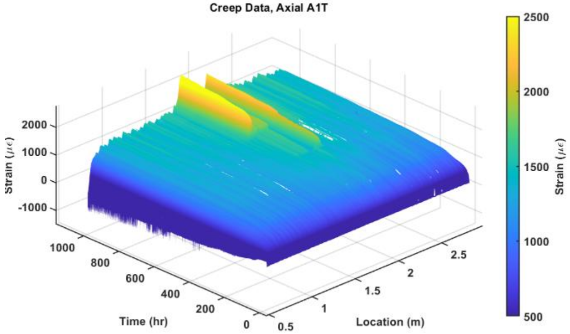
- Single optical fiber
- 1000's of sensing points
- Ultra-high spatial resolution
- Easy to install

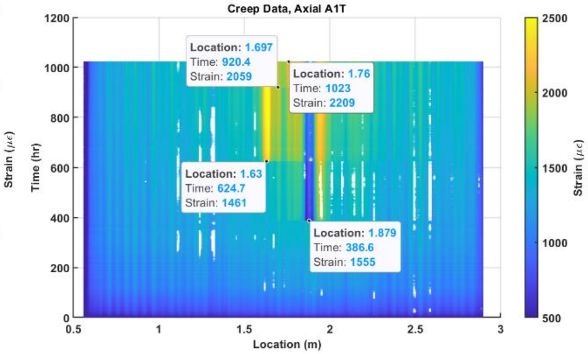
SHM Case Study: FBG / Fabry-Perot Interferometer Point Sensing for Bridge Wire Break Detection

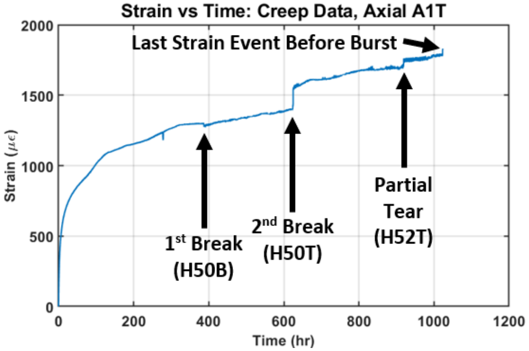
- Steel cables inside concrete structure exhibit individual wires breaks
  - Can indicate degrading health of structure
- Roosevelt Bridge in FL instrumented for wire break events through acoustic emissions
  - Two Hyperion interrogators (for FBG strain and FPI accelerometer sensors)
  - 128 fiber optic accelerometers
  - Multiplexed 8-16 accelerometer sensors per cable
- Two installed fiber optic instruments accomplished what would normally require 12 conventional systems
- Sensing coverage over 4,500 ft of bridge length
- Provided wire break event detection, categorizing, and reporting
- 24/7 health monitoring

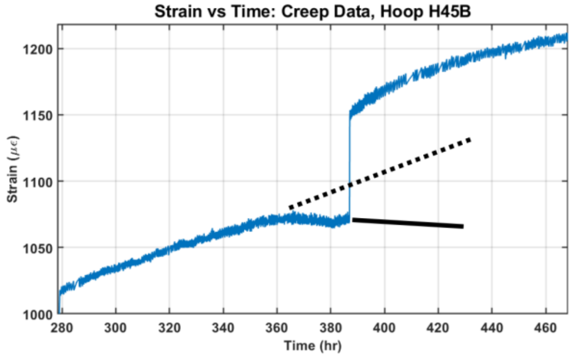
SHM Case Study: HD-FOS Strain Sensing in Inflatable Space Habitat with AI/ML Anomaly Detection

- Inflatable habitat made of Vectran webbing had HD-FOS sensors woven into webbing during loom manufacturing
- Embedded sensors provided in-situ creep monitoring during 1.5 month test at NASA Johnson Space Center
- Fiber optic sensors observed creep, strap partial tears, strap breaks, pressure drops and burst
  - 4 sensing axial webbings
  - 4 sensing hoop webbings
  - Did not need to instrument every webbing
- Patented fiber egress technique and protection



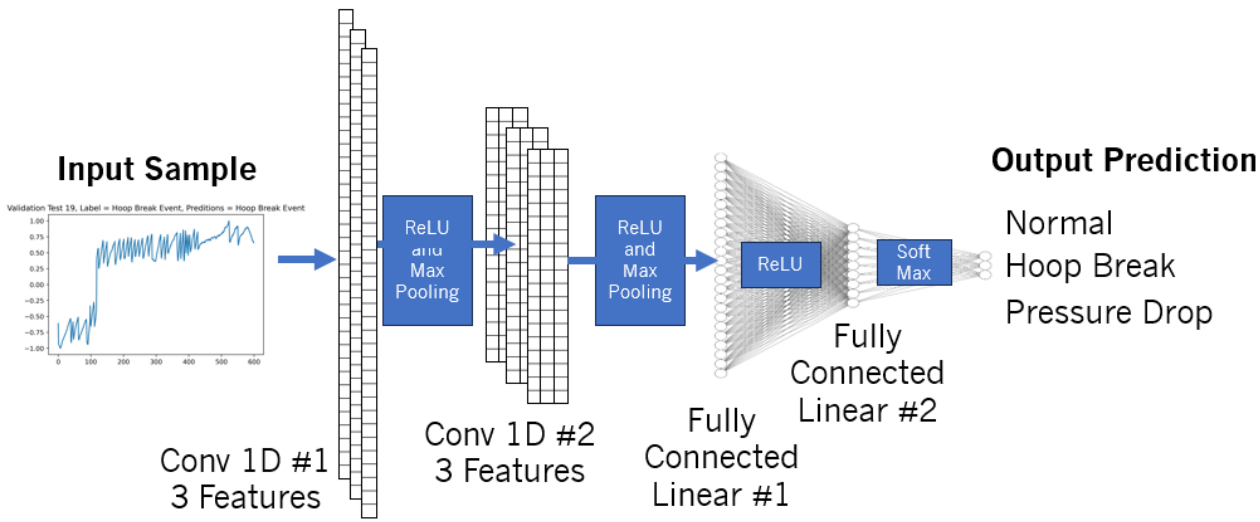


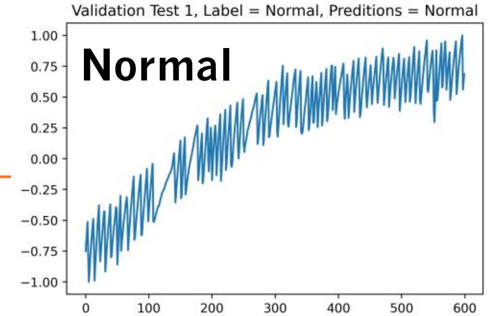


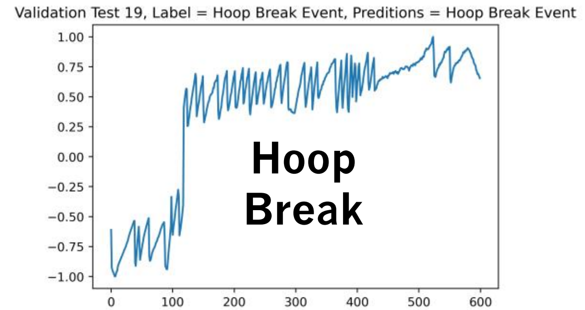


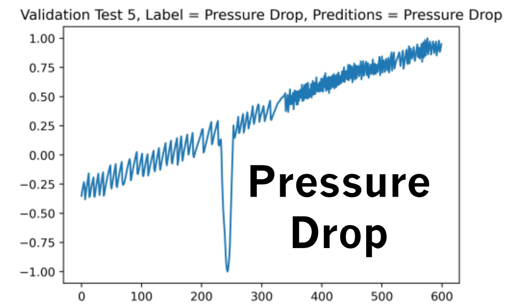
AI/ML Anomaly Detection and Classification – 1D CNN

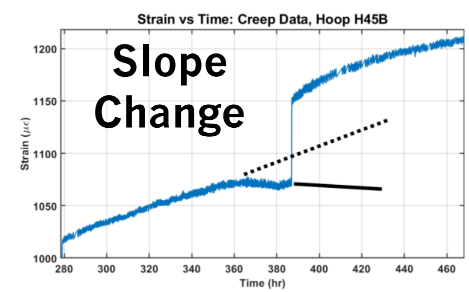
- Convolutional Neural Networks (CNN) used to recognize patterns in distributed fiber optic signals to detect and classify structural events
- 1D strain vs time data was first model developed
  - Break events and pressure drops detected
  - Added fast and slow feature detection to capture creep slope change that occurred 24 hr before structural failure
- Training data (80%) and validation data (20%) of available samples
- **99.8% accuracy** (4 misses out of 2,146 samples from validation data, not training data)



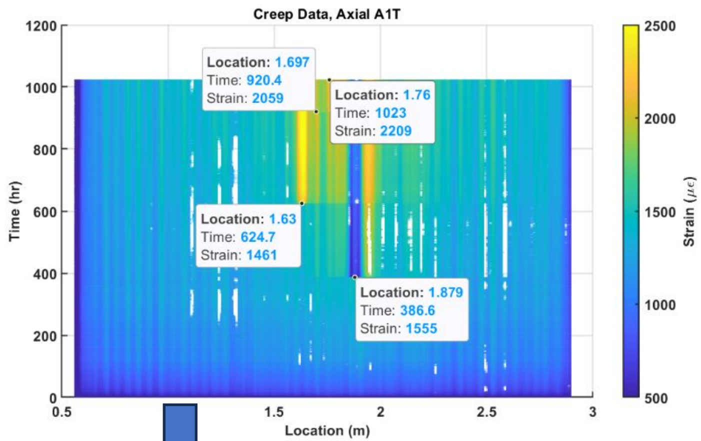




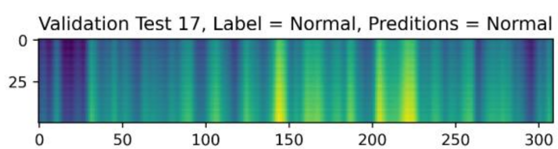




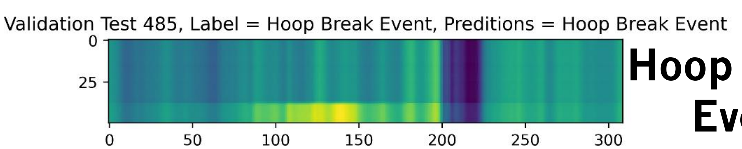
AI/ML Anomaly Detection and Classification – 2D CNN



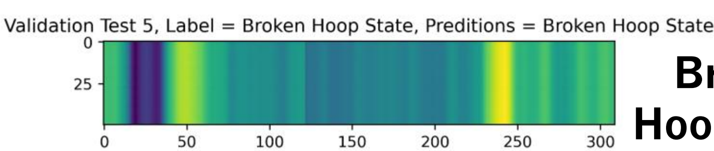
Sample snippets input for AI/ML:



Normal

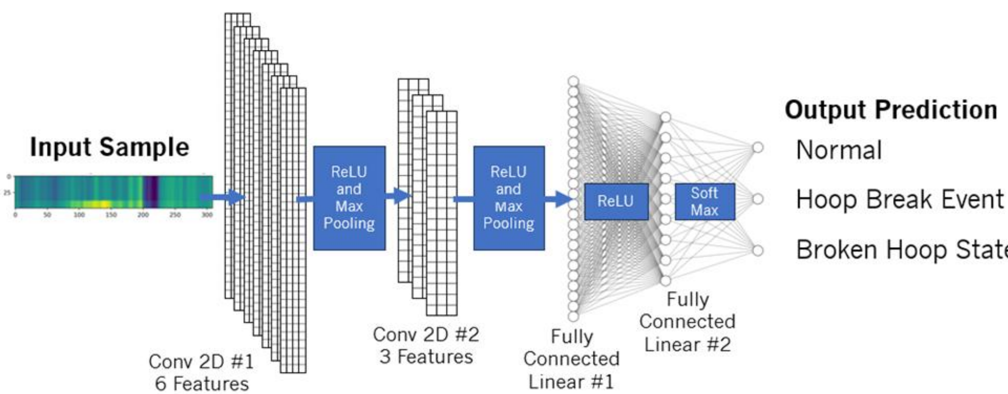


Hoop Break Event



Broken Hoop State

- 2D CNN neural network to interpret strain vs sensor length & time
- Distinguishes between persistent damage and new damage events (very difficult) in strain distributed signal
- Distributed data allows for pinpointing location of damage/fault
- **99.6% accuracy** (65 miss out of 16,068 samples)



Conclusions

- Fiber optic sensing is extremely versatile and can address virtually every infrastructure monitoring need
- Choosing the sensing technique that excels at your application is critical
  - Long-distance sensing can measure up to 100 km lengths
  - High-definition sensing can identify detailed spatial features, gradients, and anomalies
  - FBG and FPI multi-point sensing can address high-speed sensing and edge deployment
- **Distributed strain, temperature, and acoustic data is rich with features that artificial intelligence and machine learning (AI/ML) can leverage**
- **<u>There is great opportunity to further develop and deploy fiber optic sensing for infrastructure sensing!</u>**
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