“Innervated” Pipelines: A New Technology Platform for In-Situ Repair and Embedded Intelligence

PI:
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Team Members / Co-PIs:
Dr. Kevin Chen, Dr. Jung-Kun Lee, University of Pittsburgh (Pitt)
Dr. Glenn Grant, Dr. Kayte Denslow, Dr. Christopher Smith, Pacific Northwest National Laboratory (PNNL)

Project Vision
Demonstrating in-situ repair and fiber optic sensor deployment through robotic deployable cold-spray, combined with a fusion of acoustic NDE and distributed fiber optic sensing in an artificial intelligence-based classification and diagnostic framework for asset health monitoring.

Total Project Cost: $1.0M
Length: 12 mo.
The Concept: Big Picture

“Innervated” Pipelines of the Future

In-Situ Repair + Embedded Intelligence + Digital Asset Modeling

Focus of Initial 12-Month Project Efforts: Targeted Feasibility Demonstrations
(1) Cold Spray Repair Methodology, (2) Fiber Optic Embedding, and (3) Fiber Optic Installation
The Concept: Cold Spray Based Repair + Sensor Embedding

- **Cold-spray process**: Cold spray is a proven high-rate metal deposition process where metal powders (~5-45 μm particles) are combined with hot gas, accelerated to high velocity (Mach 1-4) and deposited on repair area to build up thickness.

- Fully dense, thick metal deposit, metallurgically bonded to substrate
- Can repair through-holes and “build back” corrosion allowance
- Can embed sensors in the wall for condition assessment

The concept is to make a pipe-in-a-pipe that may offer structural credits far superior to polymer liner options.
The Concept:
Advanced Acoustic NDE / Optical Fiber Methods

Propose New Advanced NDE Interrogation Techniques, and Low-Cost Cold-Spray Embedded Fiber Optics Sensing.
The Concept:
Acoustic NDE + Fiber Optics + AI / ML Fusion

Acoustic NDE / Fiber Optic Sensing Can Be Combined with AI and ML Frameworks for Pipeline Defect Localization / Classification.
The Team: Overall Project Structure

Project Organizational Chart for Year 1 Efforts

Organizational Chart

ARPA-E Program Management

Project PI:
Prof. Paul Ohodnicki
University of Pittsburgh

Industry Advisory Committee

Co-PI:
Glenn Grant
PNNL
Key Technical Lead:
Kayte Denslow
PNNL
Key Technical Lead:
Christopher Smith
PNNL

University of Pittsburgh

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Co-PI:
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Key Technical Lead:
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University of Pittsburgh

Mr. Glenn Grant (Co-PI)
Chief Scientist
App. Mat. and Manufacturing Group
Energy and Environ. Directorate

Pacific Northwest National Laboratory

Dolendra Karki
Senior Research Associate
University of Pittsburgh

Pacific Northwest National Laboratory

Dr. Kayte Denslow
Research Focus: Non-Destructive Evaluation, Novel Transducers, Acoustic Guided Wave Mode Propagation

University of Pittsburgh

Dr. Christopher Smith
Research Focus: Cold Spray, Solid Phase Joining and Processing (Friction Stir Welding), Leads projects in Robotic platform integration

University of Pittsburgh

Graduate Students (2)
University of Pittsburgh

University of Pittsburgh

University of Pittsburgh

University of Pittsburgh

University of Pittsburgh

University of Pittsburgh

University of Pittsburgh

Industry Advisory Committee

Project Leadership and Coordination
Economic Modeling
Fiber Optic Sensor Technology
Physics-Based AI-framework Training
Corrosion Sensor Technology
Cold-Spray Coating Technology and Deployment
Coating Materials and Corrosion Protection
Fiber Optic Sensor Embedding
Non-destructive Evaluation (NDE) Techniques
Digital Twin Framework Development
Physics-Based Modeling with Accelerated Solver
FEA Based Application for Defect Signatures
Coating and Sensor Valuation and Optimization
Regulatory Framework
Industrial Perspective
In-Line Inspection Data
GIS / Digital Twin Framework Interface
Team Capabilities and Contributions
Project Objectives
Primary Focus in First Year Efforts

Key Innovations to Be Pursued in year 1
- Cold-spray in-situ repair (primary year 1 focus)
- Internally deployed distributed fiber optics
- Multiphysics modeling for acoustic signatures of defects

Primary Risks to Be Mitigated in year 1
- Basic feasibility of cold spray repair (primary year 1 focus)
  - Feedstock material (cost, performance)
  - Coating quality (thickness, uniformity, permeability)
  - Deployment scenario scoping (industry advisory group)
  - Economic models of initial deployment scenarios
- Protection of fibers for internal deployment
- Need for large data sets to train AI / ML models
Project Objectives
Cold-Spray In-Situ Repair

- Selection and sourcing of feedstock materials
  - Emphasis on low-cost steel and iron feedstock (cost)
  - Quality in terms of size, uniformity, required heat treatment
  - Early process feasibility and screening

- Coating validation experiments
  - Bare steel and/or cast-iron coupons
  - Target thicknesses > 5mm, coating density >95%, Adhesion >7000psi as per ASTM C633 (Positest Adhesion testing)

- Robotic deployment tool validation
  - Establish a rotational head spray nozzle to coat pipe interior
  - Successfully coat a 10-24” diameter pipe, 4ft long, 5mm thick
  - Acoustic NDE benchmarking of coating quality
  - Transition Technology to Industry Partners in Future Years
Project Objectives
Fiber Optic Sensor Technology

- Fiber optic sensor embedding using cold spray
  - Trials of fiber optic embedding in cold spray > 3mm thick
  - Measure transmission / backscattering of embedded fibers
  - Explore coatings and protections for fiber optic sensors

- Fiber optic robotic deployment tool design and demonstration
  - Internal pipe installation on bare steel or cast-iron
  - Scaled down automated deployment tool design and demo
Project Objectives
Physics Based Modeling of Defect Signatures

- Establish representative pipeline segment models
  - Acoustic, temperature, and strain distribution – defect free
  - Characteristic distributions for representative defects
  - Sampling of expected sensing signatures for both fiber optics and acoustic NDE methods

**Inputs:** Pipeline + defect + gas transport parameters

**Computation Simulations**
- Use multi-physics model to simulate sensor response
- Accelerate simulations using reduced order modeling
- Simulate datasets of healthy & defect scenarios for training AI model

**Simulated Dataset**
- Conduct lab-scale experiments to collect sensor data for healthy & defect scenarios
- Use advanced data analytics to automate the processing of large datasets
- Collect labeled distributed sensor data for AI model training

**AI Model**
- Output: Defect detection
Project Objectives
Technology to Market

- Establishment and Meeting of Industry Advisory Group
  - Assess cold-spray coating and optical fiber embedding
  - Economic assessment
  - Regulatory considerations
  - Scoping of various deployment scenarios
- Draft / first completed technology to market plan

Industry Advisory Committee

Dewitt Burdeaux
Mat Podskarbi
Marius Ellingsen
Ruishu Wright
Kent Weisenberg

Economic Modeling, Regulatory, Deployment, Related R & D
# Project Objectives: First Year Project Timeline

<table>
<thead>
<tr>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
<th>Q4</th>
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<tr>
<td><strong>Project Management / T2M</strong></td>
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<tr>
<td>Industry Advisory Group Meeting</td>
<td>Industry Advisory Group Meeting</td>
<td>First Completed Draft T2M Plan</td>
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<tr>
<td>First Iteration of T2M Plan</td>
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| **Cold-Spray Process Development and Validation** | | | |
| Initial Coating Validation Experiments | Robotic Deployment Tool Modification | Go/No-Go: Robotic Deployment Tool Modification | |
| | Coating Validation Experiments | | |

| **Fiber Optic Sensor Deployment, Embedding, and Acoustic Modeling** | | | |
| Fiber Optic Sensor Embedding with Cold Spray | | Fiber Optic Interrogation with Acoustic Excitation | |
| Completed Fiber Optic Robotic Deployment Tool Design | | | |
Results:

Prior PNNL Motivating Cold-Spray Repair Research

- Cold Spray Repair of Hydroturbine Impellers in-situ at large hydroelectric facilities

Results indicate cold-spray repair can produce conditions with 5 to 10x improvement in cavitation erosion resistance over arc welding repair and 2 to 4x improvement over original material.

- Cold spray repair of SCC on Dry storage containers for nuclear spent fuel

Robotic platforms have been designed to support cold-spray nozzles and feed hoses and have been tested for repair of dry storage containers.
Results:
Prior Pitt Motivating Optical Fiber Sensing + AI

Ultrafast Laser Processing to Fabricate In-Fiber Devices for Low-Cost Sensing

Ultrafast (fs) Laser Processing

In Line Fabry-Perot Sensors

Discrete In-Fiber Sensor Devices Allow for Quasi-Distributed Sensing
M. Wang, P. Ohodnicki, P. Lu, K. Chen et al., Optics Express, 28 (14), 20225 (2020).

Convolutional Neural Network Supervised Learning

Discrete Acoustic Sensing Devices Combined with AI Classification Frameworks Allow for Development of Pattern Recognition Schemes (Infrastructure Security, Faults, etc.)
H. Wen, P. Ohodnicki, K. Chen et al., 2018 Asia Communications and Photonics Conference.
Challenges and Risks

Challenges

‣ Optimization of process parameters for cold-spray repair coatings and fiber optic sensor embedding
‣ Protective packaging of fiber optic sensors for cold-spray embedding internal to the pipe
‣ Development of robotic deployment strategies for both cold-spray repair and fiber optic installation and embedding
‣ Pitt and PNNL at Partial Capacity Due to COVID-19

Risk Mitigation

‣ Industry Advisor Group Engagement During Initial Feasibility Demonstrations of Year 1 to Ensure Deployment Compatibility
‣ Fiber Optic Deployment Tool Demonstration in Year 1 to Integrate with Cold-Spray Embedding in Subsequent Years
Potential Partnerships

Potential to Enhance Project Outcomes / Impacts Including:

- Identifying defects and failure modes for physics-based simulations of acoustic signatures
- Expanded capabilities for performance testing of coated pipeline materials by cold-spray
- Opportunities for field validation of distributed fiber optic sensor technology, including in-pipe integration
- Adopting deployment strategies from other technologies
Summary Slide

**Technology Summary**
- **In-Situ Pipeline Repair, Coating, and Sensor Embedding Through Robotically Deployed Cold-Spray Methods**
- **Fiber Optic Sensing and Commercial NDE Technique Synergy with Artificial Intelligence Data Analytics for Defect Identification and Localization**

**Technology Impact**
- **Unprecedented Capability for In-Situ Repair and Sensor Embedding at Scale for an Economical Cost**
- **New “Embedded Intelligence” Imparted By Real-Time Monitoring and an AI Classification System Approach**

**Proposed Targets**

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<tr>
<th>Metric</th>
<th>State of the Art</th>
<th>Proposed</th>
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<tr>
<td>Deployed Fiber Optic Sensor Cost Per km</td>
<td>&gt;$5000 / km, external to pipe</td>
<td>&lt; $500 / km, internal to pipe</td>
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<tr>
<td>Deployed Internal Coating Cost</td>
<td>Does Not Exist</td>
<td>&lt; $500 / m</td>
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**Proposed Year 2/3 Efforts Would Target:**
- Deployment of Cold-Spray, NDE, and Fiber Optic Sensing
- Development of AI-Framework, Potentially with Digital Twin
Extra Slides Follow
The Concept: Technology Elements

“Innervated” Pipelines of the Future

In-Situ Repair + Embedded Intelligence + Digital Asset Modeling

Technology Elements #1,2

- Distributed Optical Fiber Sensor and Acoustic Guided Wave NDE Fusion

Technology Element #3

- Artificial Intelligence and Machine Learning for Acoustic Signature Defect Identification / Classification

Technology Element #4

- In-Line Inspection and Surrounding Infrastructure Data (e.g. GIS)

- Digital Twin Framework Providing Central Intelligence

Technology Element #5

- Regulatory Requirements and Standards

- Cold-Spray Based In-Situ Repairs, Coatings, and Sensor Embedding

Initial 12-Month: Primary Emphasis

Initial 12-Month: Secondary Emphasis
The Concept:
Advanced Acoustic NDE Methods

Acoustic NDE is a Mature, Regulatory Approved Technique for Pipeline Monitoring

Propose New Cold-Spray Fabricated Ultrasonic Transducers and Advanced NDE Interrogation Techniques and Data Analysis.
The Concept: Distributed Optical Fiber Sensing

External Deployed Fiber Optic Sensors are Commercially Available

Custom Developed, Low-Cost Distributed Fiber Optic Sensors and Interrogators

Fiber Optic Coatings for Protection / Corrosion Sensing

Propose New Internal Deployed, Low-Cost Cold-Spray Embedded Fiber Optics and Functionalization for Corrosion Monitoring.
The Concept:
Advantages of Cold-Spray Repair Method

- Lower temperature process compared to conventional repair techniques (e.g., welding), and method of application results in reduced thermal input to area of repair
  - No heat affected zone (HAZ) that alters the microstructure of the base metal as occurs with traditional fusion-based welding operations
  - No need for post-repair stress relieving
  - No ignition hazard from flame, required pre-grinding operations, or other operations consisting of spark-generating moving parts
- Can achieve high deposition rates, on the order of 350 g/min
- No restrictions on repair thickness
- Can apply (i.e., bond) dissimilar metals
- Can be adapted to a robotic platform
The Team: People and Capabilities

Project Capabilities and Responsibilities

- Project Leadership and Coordination
- Tech 2 Market Plan
- Fiber Optic Sensor Technology
- Physics-Based AI-framework Training
- Corrosion Sensor Technology
- Cold-Spray Coating Technology and Deployment
- Coating Materials and Corrosion Protection
- Fiber Optic Sensor Embedding
- Non-destructive Evaluation (NDE) Techniques
- Digital Twin Framework Development
- Physics-Based Modeling with Accelerated Solver
- FEA Based Application for Defect Signatures
- Coating and Sensor Valuation and Optimization
- Regulatory Framework
- Industrial Perspective
- In-Line Inspection Data
- GIS / Digital Twin Framework Interface

Prof. Paul Ohodnicki (PI)
Associate Professor
Mechanical Eng. & Materials Science
Electrical and Computer Eng.

Prof. Kevin Chen (Co-PI)
Professor
Electrical and Computer Eng.

Fiber Optic Sensors
Photonics
Distributed Interrogation
AI / Sensor Fusion

Prof. Jung-Kun Lee (Co-PI)
Professor
Mech. Eng. & Materials Science

Functional Materials
Thin Film Coating (ALD)
The Team: Laboratory Facilities

Fiber Optics Facilities

Thin Film Coating / ALD Facilities

Atomic Layer Deposition, Sputtering / Evaporation, Wet Chemistry

Structural / Metallurgical Facilities

Distributed Interrogation Systems, Ultrafast fs-laser Processing, Photonics and Microwave Instrumentation

Structural Characterization (SEM, TEM, XRD), Metallurgical Testing
The Team: People and Capabilities

Mr. Glenn Grant (Co-PI)
Chief Scientist
Applied Materials and Manufacturing Group
Energy and Environment Directorate

Dr. Kayte Denslow
Research Focus: Non-Destructive Evaluation, Novel Transducers, Acoustic Guided Wave Mode Propagation

Dr. Christopher Smith
Research Focus: Cold Spray, Solid Phase Joining and Processing (Friction Stir Welding), Leads projects in Robotic platform integration

Project Capabilities and Responsibilities

- Cold-Spray Coating Technology
- Cold-Spray Coating Deployment
- Coating Materials
- Corrosion Protection
- Fiber Optic Sensor Embedding
- Non-destructive Evaluation (NDE)

Research Focus: Advanced manufacturing, forming, joining, thermomechanical processing. Leads programs in Solid Phase Processing
The Team: Laboratory Facilities

**Pipeline Test Loop Facilities**

**NDE / EMAT Facilities Summary**

Cold Spray Facility Summary
- VRC GEN 3 High Velocity System
- Applicator end effector nozzle on stationary robot platform
- Rotary Positioning System
Cold Spray Project Objective

- Develop the process to apply a fully dense metal deposit of >5 mm thickness to the inside of a legacy pipeline to repair damaged material, build back corrosion allowance, and potentially heal small through-wall penetrations...all without excavation.

- Benchmark the process speed and material costs (gas and powder) on a 4 foot length of pipe 10 -12 inches in diameter.

- Transfer the process, materials, and equipment designs to commercial entities to implement the process on a robotic crawler capable of travelling inside a pipe.
# Cold Spray Project Approach

<table>
<thead>
<tr>
<th>Title</th>
<th>Task Description (76716)</th>
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<tbody>
<tr>
<td>Task 1 PM</td>
<td>Project Management</td>
</tr>
<tr>
<td>Task 2 Cold Spray Development Flat Plate</td>
<td>Apply cold spray coating to bare steel / cast iron coupons (Milestones M1.2,M2.1)</td>
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<tr>
<td>Task 3 Cold Spray Development Pipe Inner subsections</td>
<td>Apply cold spray coating to bare steel / cast iron pipe sections, develop nozzle for inside diameter CS (Milestone 2.2)</td>
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<tr>
<td>Task 4 Characterization</td>
<td>Characterize cold spray coating (1) Coating thickness by cross-sectional optical microscopy. 2) Coating density of &gt;95% will be confirmed using optical microscopy and image analysis. 3) Mechanical adhesion strength greater than 7000 psi by Positest Adhesion testing (ASTM C633) (Milestone M2.3)</td>
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<tr>
<td>Task 5 Pilot Scale Demo</td>
<td>Pilot scale demonstration of robotically-applied cold spray onto 10-in. dia. 4 ft long Pipe  (Milestone M2.4)</td>
</tr>
<tr>
<td>Subtask 5a</td>
<td>Verification of deposit integrity by UT NDE (Milestone M2.4)</td>
</tr>
<tr>
<td>Task 6 Fiber optic sensor embedding using cold spray</td>
<td>Fiber optic sensors embedded within cold-spray coatings &gt;3mm thickness on bare steel or cast-iron coupons. Transmission reduction &lt;50% for embedded fibers as compared to pristine fibers measured by backscatter reflectometry (Milestone M3.1)</td>
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Cold Spray Setup and Process Parameters

- Metal powder
  - Material
  - Density
  - Particle size and shape
  - Particle size distribution (PSD)
  - Hardness

- Cold spray process input parameters
  - Carrier gas (He or N₂)
  - Carrier gas temperature at entrance to nozzle
  - Carrier gas pressure
  - Powder feeder speed
  - Powder feed gas flow rate
  - Cold spray gun orientation
  - Nozzle standoff distance

- Nozzle
  - Geometry
  - Material
  - Application gun (VRC “Barrel Applicator”)

- Substrate
  - Surface preparation
    - Cleaning
    - Texture
    - Bonding coat
  - Temperature

- Raster Pattern
  - Path
  - Step-over distance / spray overlap
  - Number of layers
  - Robot travel speed

VRC Systems Cold Spray HMI
Results:
Prior Pitt Motivating Fiber Optic Sensor Embedding

Additive Manufacturing to Embed Optical Fibers for Temperature Distribution Monitoring

Monitoring of the Temperature Distribution Internal to a Solid Oxide Fuel Cell

K. Chen, P. R. Ohodnicki, et al., Currently Under Review
Results:
Prior Pitt Motivating Distributed Optical Fiber Sensing

Ultrafast Laser Processing to Control Degree of Backscatter By Nanograting Formation

Tunability of Backscatter
- Laser Power
- Laser Scanning Speed

Trade-off Between Signal to Noise and Loss

Optimization of Signal to Noise Ratio and Stability of Backscatter By Advanced Fiber Processing Techniques Using Ultrafast Laser Processing

Results:
Prior VRC Metal Systems Repair Demonstrations

Stopping Active Pressurized Leaks (1000psi)

Small ID Corrosion Repairs

Portability of Cold Spray (Hand Operated and Robotic)
Results:
Prior Pitt Motivating Distributed Optical Fiber Sensing

Ultrafast Laser Processing to Fabricate In-Fiber Devices for Low-Cost Sensing

Ultrafast (fs) Laser Processing

In Line Fabry-Perot Sensors

In Line Fabry-Perot Sensors Array with Different Cavity Lengths

Discrete In-Fiber Sensor Devices Allow for Quasi-Distributed Sensing

M. Wang, P. Ohodnicki, P. Lu, K. Chen et al., Optics Express, 28 (14), 20225 (2020).
Low-Cost Distributed Sensing Integrated with AI Classification Frameworks

Discrete Acoustic Sensing Devices Combined with AI Classification Frameworks Allow for Development of Pattern Recognition Schemes (Infrastructure Security, Faults, etc.)

H. Wen, P. Ohodnicki, K. Chen et al., 2018 Asia Communications and Photonics Conference.
Results:

Prior Motivating Distributed Optical Fiber Sensing

Application of Distributed Strain Sensing for Local Corrosion Detection

- Internal pressure = 1MPa
- Axial strain of optical fiber

Experimental Setup

Pipe cross section

Pipeline internal corrosion monitoring (Jiang et al, Struct Control Health Monit. 2017)
Results:
Prior Pitt Motivating AI Based Reduced Order Modeling

Physics-Based AI Approach to Reduced Order Modeling of Complex Physical Phenomena

- Data sampling
- Dimensionality reduction
- Modes

Response Surface Models (RSM)

ROM Result:

Accelerated Simulation of Sensing Responses for Defects and Pipeline Configurations to Accelerate AI-Framework Training for Defect Localization / Identification