AI-Enabled Robots for Automated Nondestructive Evaluation and Repair of Power Plant Boilers

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The project goal is to develop integrated autonomous robots that are equipped with nondestructive evaluation (NDE) sensors to perform real-time inspection of boiler furnace walls, operate repair devices to achieve live repair, and use artificial intelligence (AI) to enable smart data analysis and autonomy.

- Boiler failures can cause loss of life and safety issues, cost hundreds of thousands of dollars in equipment repairs, property damage, and production losses, as well as drive up the cost of electric power.
- Failures can be prevented by performing regular maintenance.
- Boiler maintenance is dangerous on scaffolding in confined space inside a boiler, and time-consuming due to the large area of vertical structures and tremendous effort needed for scaffolding.
- This project aims to provide a robotics solution to automate boiler maintenance.
This project mainly aligns with the Fossil Energy Objective 2.2: 

Advance technologies to improve the efficiency, reliability, emissions, and performance of existing fossil-based power generation, by developing “… advanced sensors and controls to help increase coal plant efficiency, reduce forced outages, and avoid downtime related to equipment failures…”
Technology Benchmarking

<table>
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<tr>
<th>Current Practice</th>
<th>Limits</th>
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<tr>
<td>Manual maintenance</td>
<td>Safety risks caused by environment hazards and climbing up scaffolding, time-consuming to mount/dismount scaffolding, often slow and inaccurate inspection.</td>
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<tr>
<td>UAV-based inspection</td>
<td>Limited payload and operation time, requirement of human control (auto-pilot not feasible yet), dependence on wireless communication, typically only visual inspection (nondestructive inspection and repair not feasible yet).</td>
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<tr>
<td>Robotic inspection crawlers</td>
<td>Typically incapable of repair, requirement of constant remote control (no full autonomy yet), no AI for smart autonomy and predictive analysis.</td>
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Current Status of Project

- Mines and MSU work on the proposed project of designing AI-enabled robots for automated boiler nondestructive evaluation and repair.
- We also work with industry partners from Xcel Energy and EnergynTech to design experiments and seek industry feedback.
# Project Description and Objectives

## Project Objective Overview
- **NDE**: Designing nondestructive evaluation sensors for crack detection.
- **Repair**: Designing repair tool and control protocols for crack repair.
- **Robotic platform**: Integrating NDE sensors and repair tools on a mobile robot.
- **Artificial intelligence**: Designing AI methods for smart data analysis and autonomy.

## Objectives

<table>
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<tr>
<th>Objectives</th>
<th>Lead</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
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<td>Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3</td>
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<tr>
<td>NDE Sensing and Assessment</td>
<td>Deng &amp; Udpa (MSU)</td>
<td>NDE probe design</td>
<td>Signal processing</td>
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<td>Repair Device Design and Control</td>
<td>Yu &amp; Liu (CSM)</td>
<td>Integrated repair sys.</td>
<td>Repair protocol</td>
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<tr>
<td>Robotic Platform Design</td>
<td>Petruska (CSM)</td>
<td>Robot retrofit for vertical motion</td>
<td>Cleaning design</td>
<td>NDE integration on robot</td>
<td>Repair integration on robot</td>
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<tr>
<td>Artificial Intelligence Development</td>
<td>Zhang (CSM)</td>
<td>3D mapping and information fusion</td>
<td>Spatiotemporal damage tracking</td>
<td>Predictive damage analysis on robot</td>
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**Last review 05/13/2021**
Prior Achievements: NDE Sensor

NDE Probe Design

- An eddy current (EC)-based array sensor was designed which showed high scanning speed and detection accuracy.

Steel Sample (A108):
The width of the fabricated cracks is 200 μm and 400 μm

Diameter of the coil is 0.5 (unit: cm)

8 channel EC coil array

Data fusion scanning result

NDE Signal Processing

- Signal processing methods that extract crack parameters for localization and size estimation were designed.

Steel sample for testing

Signal processing for crack detection

Signal processing for depth estimation
Prior Achievements: Repair Tool

**Integrated IHA-FSW Repair Tool**
- An induction heating (IH) assisted friction stir welding (FSW) repair tool was designed, implemented, and tested in collaboration with EnergynTech Inc.
- IH serves as a preheating source that reduces the vertical force during FSW process by about 20%.

**Repair Protocol**
- Testing repair conditions were determined through surface morphology characterization, that are 500 rpm and 80 mm/min without preheating, and 400 rpm and 70 mm/min with 15kW induction heating power.

- Line scan early stage of IHA-FSW
- Line scan later stage of IHA-FSW

- FSW without preheating: 500 rpm & 80mm/min

- IHA FSW: 400 rpm, 70mm/min & an induction heating power of 15kW

- A108 steel plate samples
Prior Achievements: Robotic Platform

**Robot Retrofit for Vertical Navigation**
- We modified a tracked mobile robot to include magnets on track surfaces to attach to a vertical metal surface.

**Cleaning Tool Design**
- We developed a brush cleaning mechanism for metal surface cleaning by modifying off-the-shelf cleaning tools.
Prior Achievements: Artificial Intel (AI)

3D Mapping and Information Fusion
- Iterative closest point (ICP) algorithms build multi-layer maps by matching and overlaying adjacent frames of 3D point clouds from LiDAR.
- The method has been evaluated initially in dark, confined environments with sparse features.

Spatiotemporal Tracking
- We developed a voxel-based representation learning method for robots to recognize places, correct mapping errors, and perform localization during execution.
- We are developing methods to represent landmarks as a graph to fuse visual-spatial information for crack tracking.
NDE Sensor Integration

- An eight channel NDE sensor is attached to the bottom of gantry mechanism and scans along two dimensionalities at sub-millimeter level precision.
- The gantry system is connected with and towed by a magnetic tracked robotic platform.
- This design allows us to obtain accurate positioning data for precise scan localization and repair.

Scan Image Reconstruction

Gantry system for NDE sensor and repair tool integration

Robotic Platform
NDE Sensing Evaluation

- The portable NDE sensor with an 8-channel high-sensitivity and efficient sensor array was tested.
- The crack localization and size estimation information can be extracted by signal processing.

The magnitudes change at the resonating frequency and the Pareto front of maximizing the scanning area and the sensitivity of the sensor.

Normalized frequency shifts with different lift-off distance of the eddy current sensor shows good scanning ability of the sensor.
Offboard Repair Evaluation

- Three FSW repairs were performed on pre-machined cracks with widths from 0.2mm up to 0.8mm on the A108 steel plate.
- A W-Re tool with a pin length of 2.3mm and a shoulder diameter of 10mm was employed.
- Optimal repair parameters: 500 rpm rotation speed, 80 mm/min travel speed, 20mm/min plunge speed, 3s dwell time, and 45mm travel distance.
- Plunge depth were adjusted to accommodate the void volume of the cracks:
  - The repair on 0.2mm wide crack demonstrates the detrimental effect of insufficient penetration depth.
  - The other two cases demonstrate satisfactory repairs with proper penetration depths.
Optical microscopic examinations showed good quality welds in repairs without obvious defects. The repair depth is up to ~1.6mm using the pinless tool. The tool diameter is 10mm. Deeper repair can be enabled with longer pin length.

Cross-sectional microstructural characterization on repairs (a) without preheating (FSW); and (b) with preheating (IHA-FSW)

FSW without preheating: 500 rpm & 80mm/min

IHA FSW: 400 rpm, 70mm/min & 15kW IH
Progress on Repair Tool Integration

- The gantry system and the repair tool is designed, machined, assembled and ready for onboard testing.
- Features of the gantry system include:
  - Maneuverable NDE sensor housing with suspension
  - Heavy duty 11.5 Amp Milwaukee drill press
  - Robust 6800 lbf electromagnet base
  - High accuracy (< +/- 0.5 mm) ball screws
**Ridge Classifier**
- Data Preprocessing/Feature Extraction
  - Images are converted to grayscale
  - Techniques in computer vision detect edges
  - Find contours of each edge
  - Crop image at bounding rectangle
  - Extract features of interest

- Regularization
  - $\min_w \|y^T - w^T x\|^2 + \alpha \|w\|^2$
    - $x =$ feature vector
    - $w =$ learned weight matrix
    - $y =$ observations
    - $\alpha =$ regularization hyperparameter
    - Goal: minimize objective function
- Binary classifier predicts crack based on positive or negative regression

**Convolutional Neural Network**
- Uses a binary cross entropy loss as the classification has two options (crack or no crack)
- Uses gradient descent optimization algorithm
- Trained for 5 epochs which reached 99% validation accuracy
- 11-layer neural network
  - 4 convolutions, rectified linear activation
  - 3 maximum pooling
  - 1 flatten
  - 3 dense layers
Software System Integration

- Ubuntu 18.04 operating system on Nvidia Jetson TX2
- Software is managed through the Robot Operating System (ROS)
  - ROS allows for efficient management of code
  - Software is organized into “nodes” which can communicate
- AI Nodes
  - Odometry Fusion: Extended Kalman filter for accurate odometry
  - Image Reconstruction: Fuses odometry and NDE data to obtain scan image
  - Damage Classification: Uses trained ML model to classify damage
  - Damage tracking and Mapping: Robot localization and damage location tracking using semantic segmentation

Semantic segmentation
- Classifies damage using Mask R-CNN
- Generated pixel mask is used to localize damage

Software System Architecture

- Perception: sensing and data acquisition.
- Cognition: AI, robot localization and damage tracking.
- Action: Control of robot motors and tooling machinery
Accomplishments

• Project accomplishments:
  ▪ A portable NDE sensor has been designed that integrated on a robot. The sensor does not only work for boiler inspection but also potentially offers evaluation information for other material or component in a hazard environment.
  ▪ Repair protocol has been identified and tested in standalone experiments, which is being used for re-designing a portable onboard repair tool for a robot platform.
  ▪ AI algorithms have been developed for environment mapping, robot localization, and crack detection and tracking.

• Publication: Related research topics from this project was published at multiple conferences on NDE and robotics, including ENDE, ISEM, ICRA and IROS.
  ▪ 2020-Dr. Zhenzhen Yu and Dr. Hao Zhang were promoted to Associate Professor with tenure at Colorado School of Mines.
Preparing Project for Next Steps

**Market Benefits**

- Market benefits include limiting the need to send humans to difficult-to-access or hazardous areas, enabling automated inspection and repair, avoiding time consuming scaffolding, smartly collecting comprehensive and organized data.
- Impacts can be tremendous in terms of the time and cost savings, reducing the risk for humans, and increasing boiler reliability, usability, and efficiency.

**Next Steps**

- More data will be needed (e.g., obtained through simulation) to training AI and machine learning methods we are developing.
- Integrating an AI software system with the complex robot platform (with perception sensors, NDE sensors, repair tools, and two onboard embedded computers) for smart autonomy is last big challenge to address.
- We will work with our industrial collaborators from EnergynTech and Xcel Energy to discuss real-world testing and conduct customer discovery.
Concluding Remarks

- Proposed Research: integrated *autonomous robots* that are equipped with NDE sensors to perform *real-time inspection*, operate repair devices to achieve *live repair*, and use *artificial intelligence* to enable smart data analysis and autonomy, in order to address cracks on boiler furnace walls.
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