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

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NATIONAL ENERGY TECHNOLOGY LABORATORY

U.S. DEPARTMENT OF ENERGY

#DE-FE0031650

# Project Description and Objectives

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## Purpose of Project

- 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.

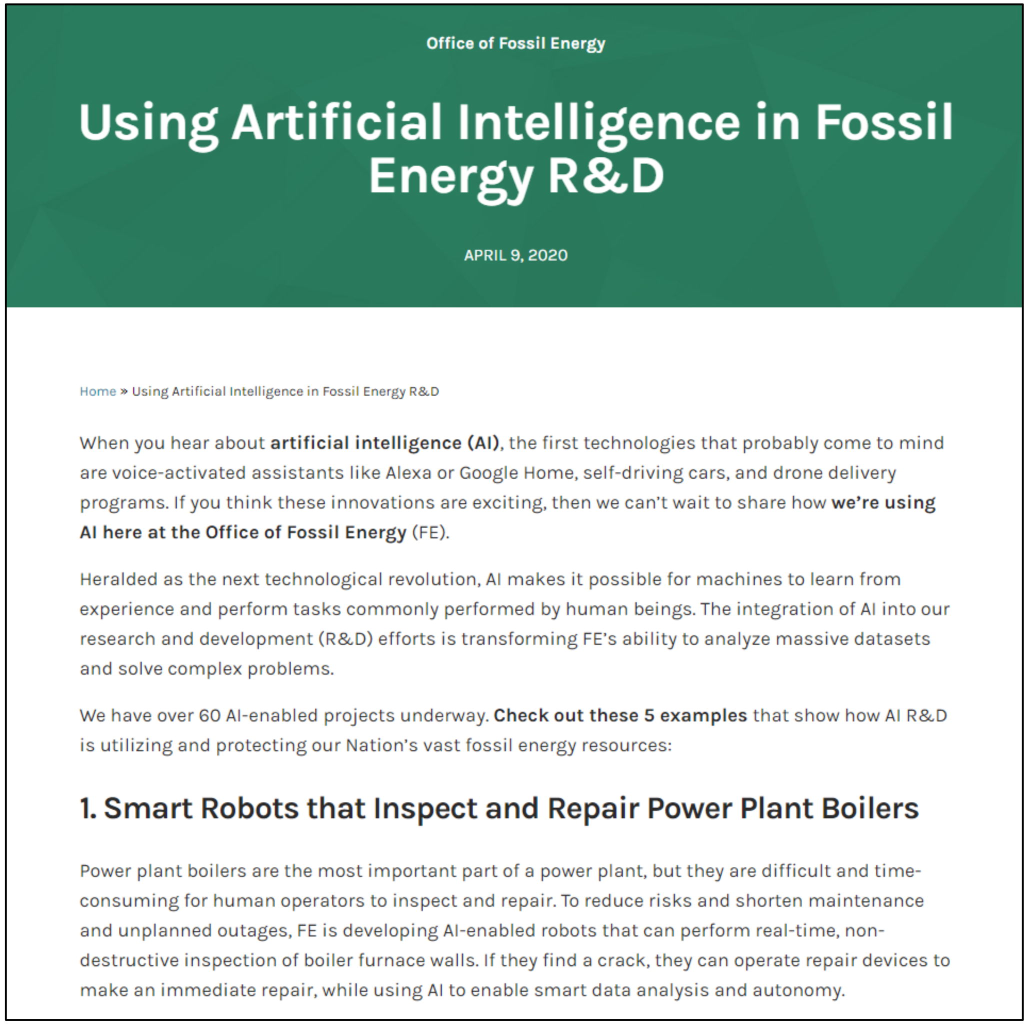
# Project Description and Objectives

## Strategic Alignment to FE Objectives

- 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*…"



Office of Fossil Energy

# Using Artificial Intelligence in Fossil Energy R&D

APRIL 9, 2020

Home » Using Artificial Intelligence in Fossil Energy R&D

When you hear about **artificial intelligence (AI)**, the first technologies that probably come to mind are voice-activated assistants like Alexa or Google Home, self-driving cars, and drone delivery programs. If you think these innovations are exciting, then we can't wait to share how **we're using AI here at the Office of Fossil Energy** (FE).

Heralded as the next technological revolution, AI makes it possible for machines to learn from experience and perform tasks commonly performed by human beings. The integration of AI into our research and development (R&D) efforts is transforming FE's ability to analyze massive datasets and solve complex problems.

We have over 60 AI-enabled projects underway. **Check out these 5 examples** that show how AI R&D is utilizing and protecting our Nation's vast fossil energy resources:

## 1. Smart Robots that Inspect and Repair Power Plant Boilers

Power plant boilers are the most important part of a power plant, but they are difficult and time-consuming for human operators to inspect and repair. To reduce risks and shorten maintenance and unplanned outages, FE is developing AI-enabled robots that can perform real-time, non-destructive inspection of boiler furnace walls. If they find a crack, they can operate repair devices to make an immediate repair, while using AI to enable smart data analysis and autonomy.

# Project Description and Objectives

NATIONAL ENERGY TECHNOLOGY LABORATORY

## Technology Benchmarking

| Current Practice | Limits |
|---|---|
| Manual maintenance | Safety risks caused by environment hazards and climbing up scaffolding, time-consuming to mount/dismount scaffolding, often slow and inaccurate inspection. |
| UAV-based inspection | 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). |
| Robotic inspection crawlers | Typically incapable of repair, requirement of constant remote control (no full autonomy yet), no AI for smart autonomy and predictive analysis. |

## 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 Update

NATIONAL ENERGY TECHNOLOGY LABORATORY

## 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.

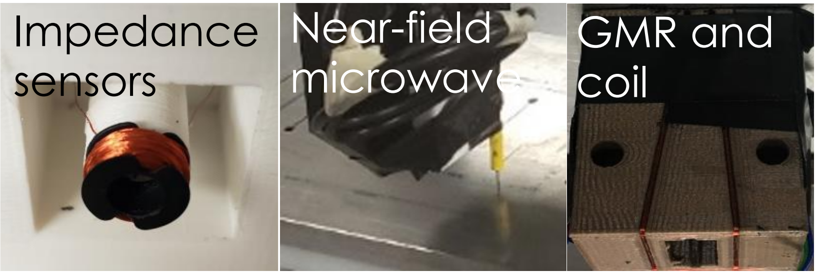
| Objectives | Lead | 2018 | 2019 | | | | 2020 | | | | 2021 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 |
| NDE Sensing and Assessment | Deng & Udpa (MSU) | NDE probe design | | | | Signal processing | | | | [redacted] | | | |
| Repair Device Design and Control | Yu & Liu (CSM) | Integrated repair sys. | | | | Repair protocol | | | | [redacted] | | | |
| Robotic Platform Design | Petruska (CSM) | Robot retrofit for vertical motion | | | Cleaning design | | NDE integration on robot | | | Repair integration on robot | | | |
| Artificial Intelligence Development | Zhang (CSM) | 3D mapping and information fusion | | | | Spatiotemporal damage tracking | | | | Predictive damage analysis on robot | | | |

08/27/2020

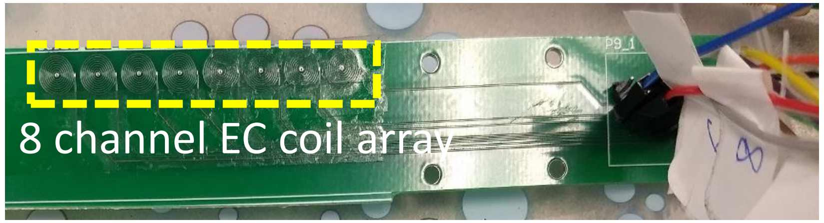
# Project Update: NDE Sensor

## NDE Probe Design

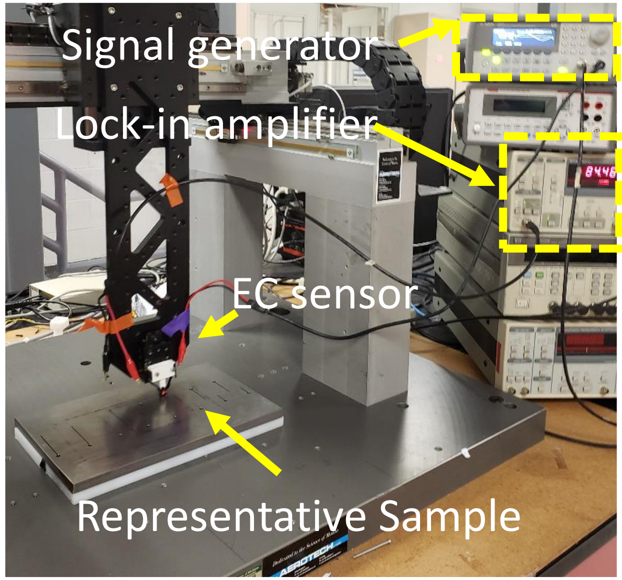
- High-sensitivity and efficient NDE sensors were designed, fabricated and tested in laboratory. Multi-modal NDE sensors were tested on multiple samples.
- Considering the scanning speed and detection accuracy, the eddy current (EC)-based array sensor was identified.



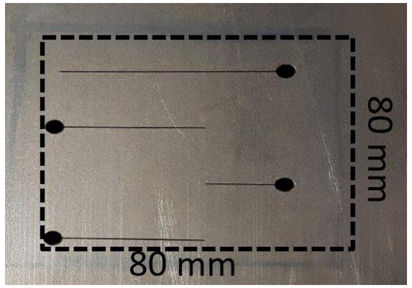

Multi-modal sensors



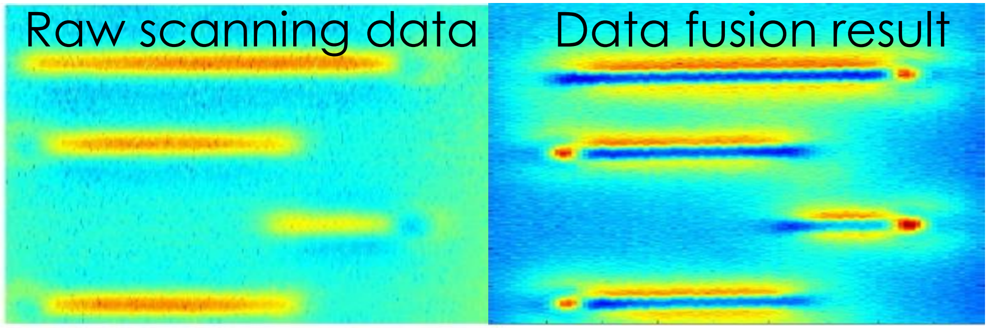

Size of the array sensor is 1.5x17.2, Diameter of the coil is 0.5 (unit: cm)

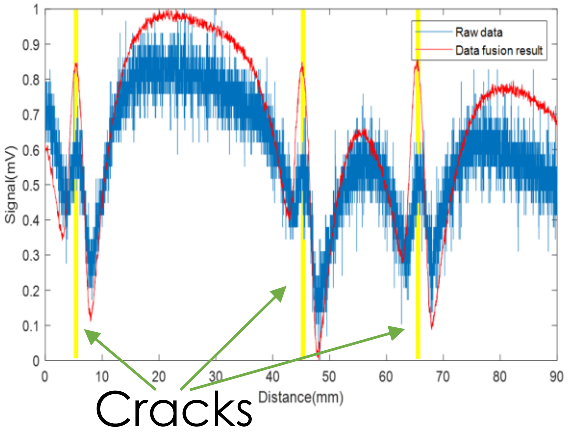



3D scanning gantry and EC sensor testing




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



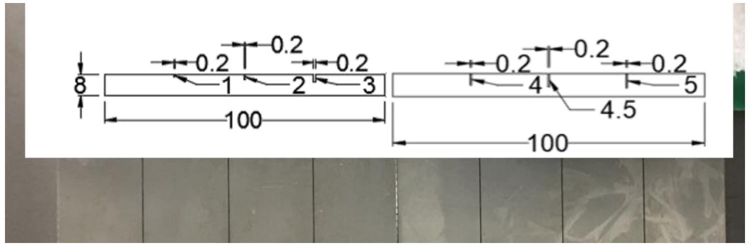

Good SNR can be observed from the plot. Yellow shaded area represent the location of the cracks

# Project Update: NDE Sensor

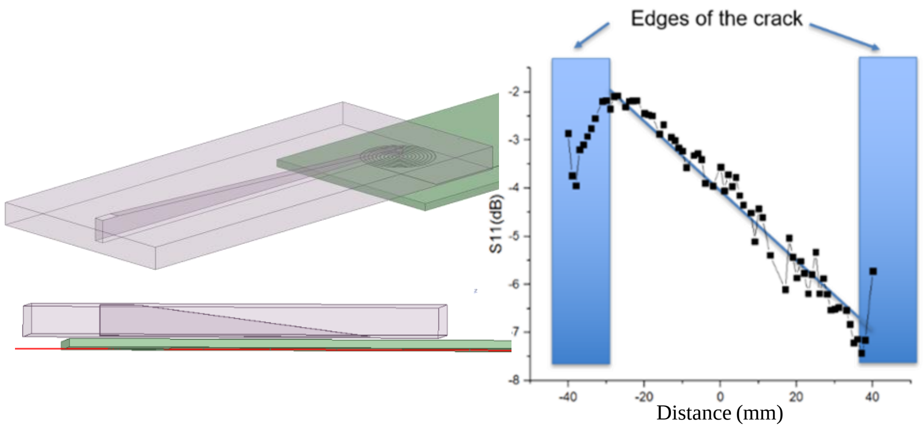
NATIONAL ENERGY TECHNOLOGY LABORATORY

## NDE Signal Processing

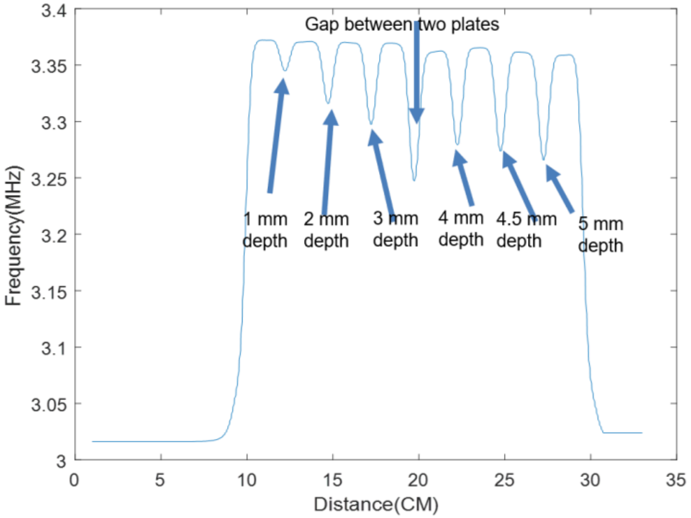
- Simulation models were designed and analyzed to provide an understanding of sensing signals and crack detection, as well as to generate training data to train and evaluate AI methods.
- Signal processing methods that extract crack parameters for localization and size estimation are under development.



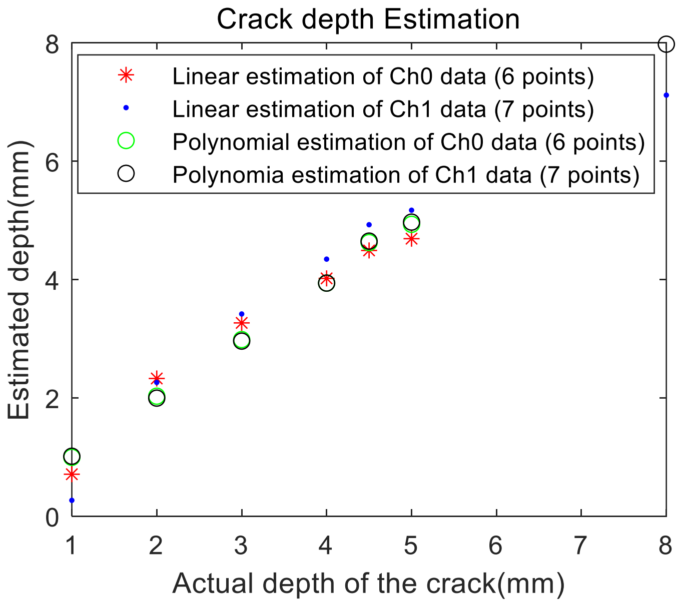

Steel sample for testing




Simulation models and results of the steel sample with wedge shaped cracks. As the sensor moving from one end to the other end, the amplitude of the S11 decreases as the depth of crack increases




Signal processing results from NDE sensors. The resonant frequency shows same trend as the simulation

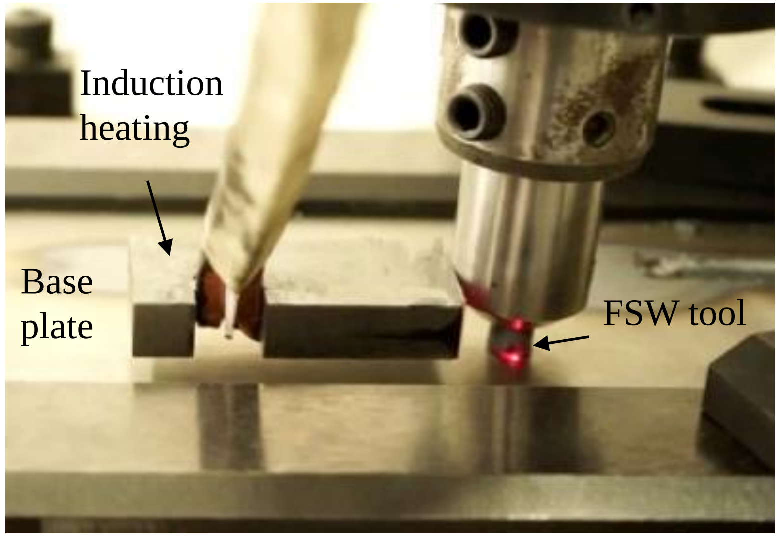



The estimation of the crack depth using different regression methods

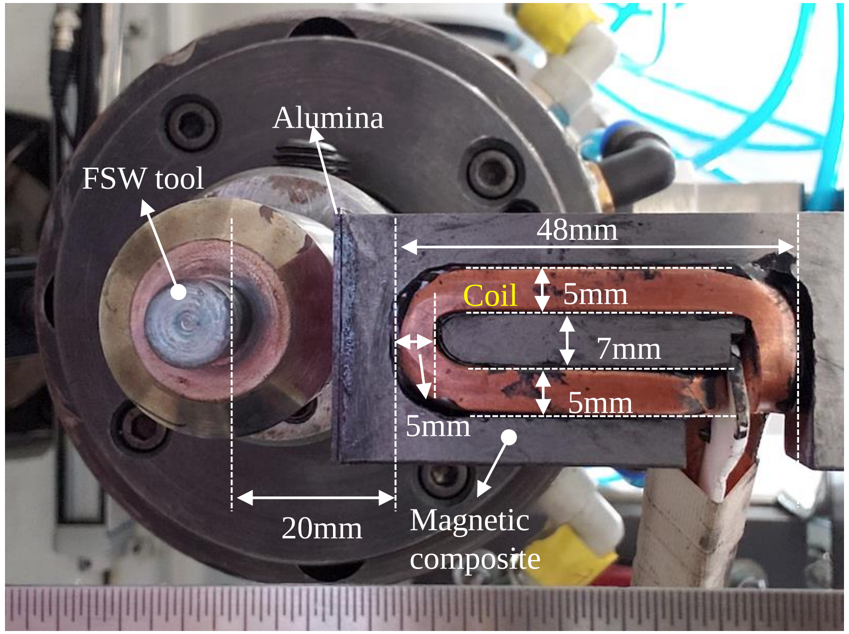
# Project Update: Repair Tool

## 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%.

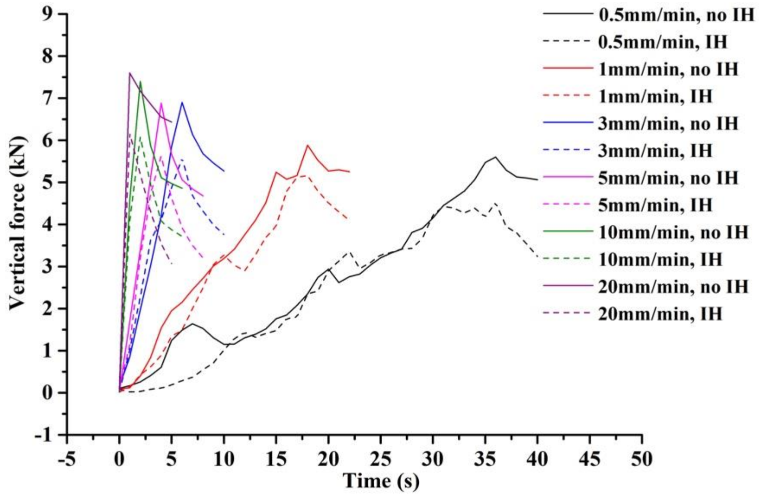


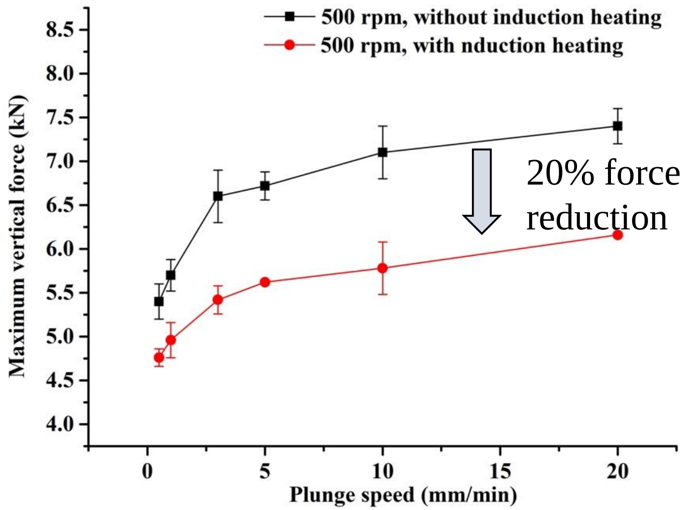

Side View




Bottom View

Effect of plunge speed & preheating

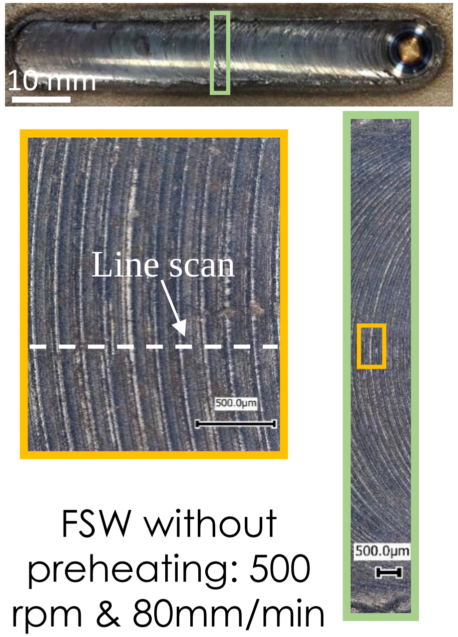


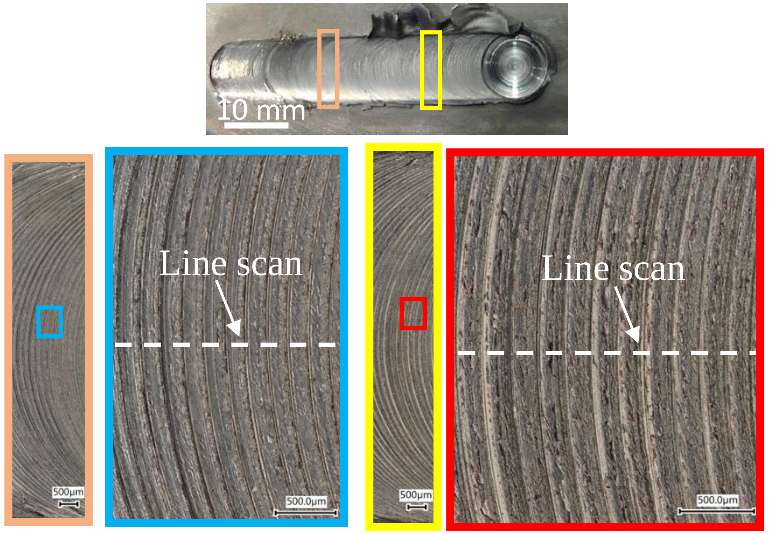
# Project Update: Repair Tool

## Repair Protocol

- Testing repairs were performed on a flat A108 steel plate with and without preheating using a pinless tool.
- 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. Plunge depth is 0.15 mm in both cases.

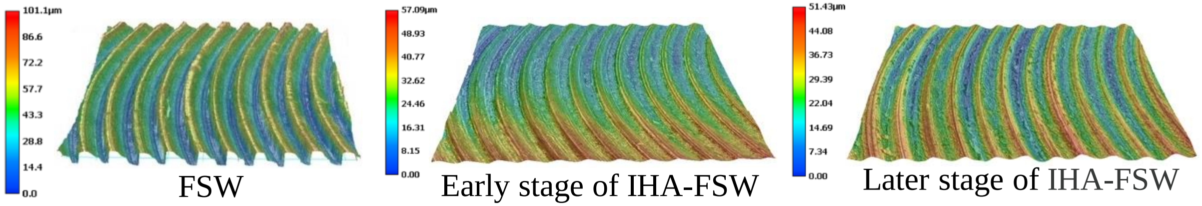


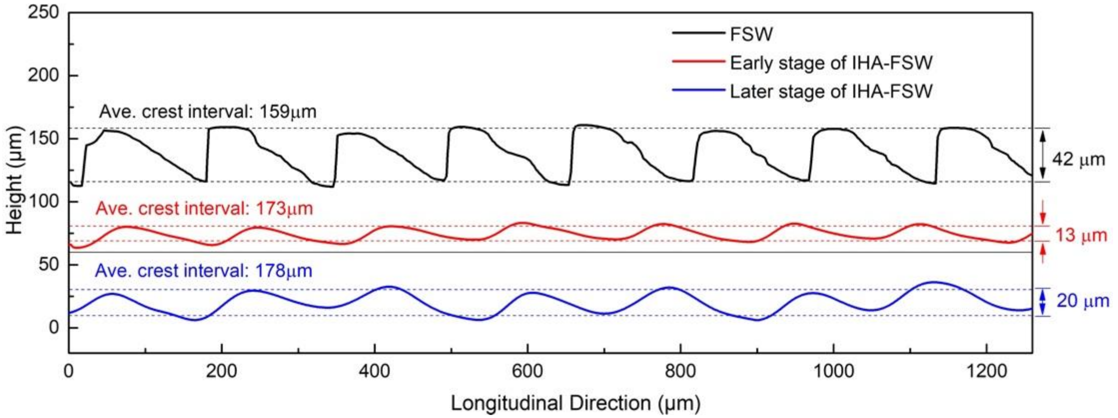

FSW without preheating: 500 rpm & 80mm/min




Early stage of IHA-FSW Later stage of IHA-FSW

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




The intervals between neighboring wave crests of the weld surface can be calculated by:

FSW: d=v/ω= (80 mm/min) / (500 rev/min) =160 µm/rev

IHA FSW: d=v/ω= (70 mm/min) / (400 rev/min) =175 µm/rev

Preheating assisted to generate a smoother surface morphology than FSW process. Excessive heating at early stage of IHA-FSW process leads to reduced wave height.

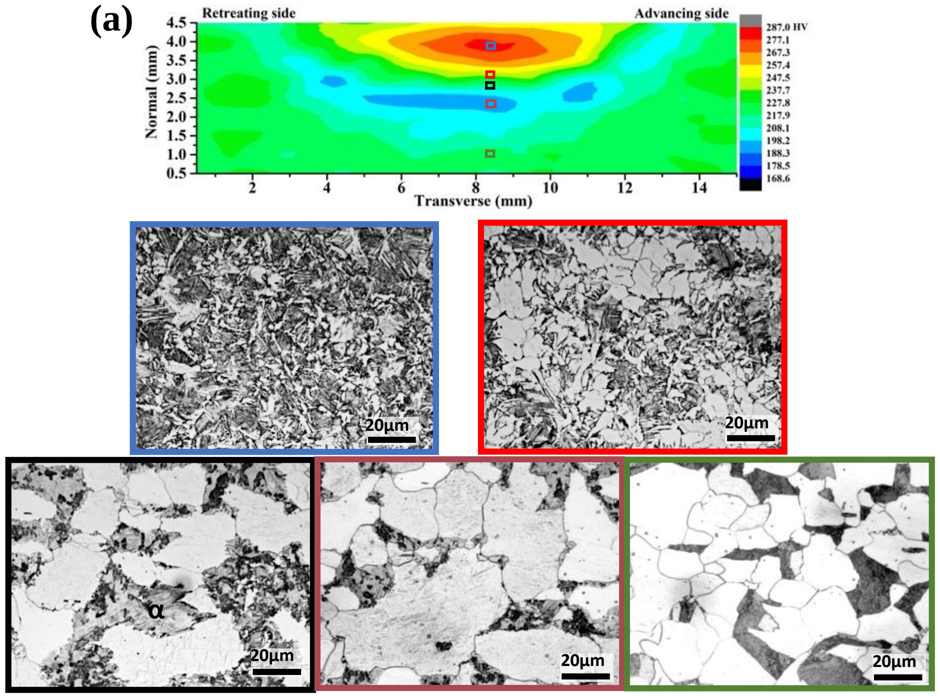
# Project Update: Repair Tool

NATIONAL ENERGY TECHNOLOGY LABORATORY

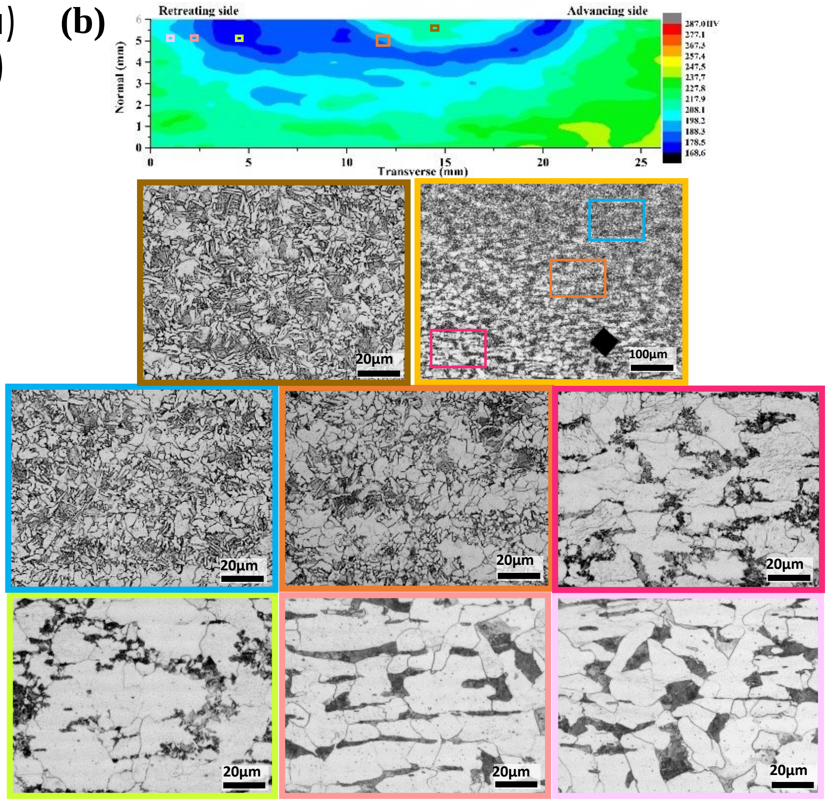
## Metallurgical Characterization for Repair Evaluation

- 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

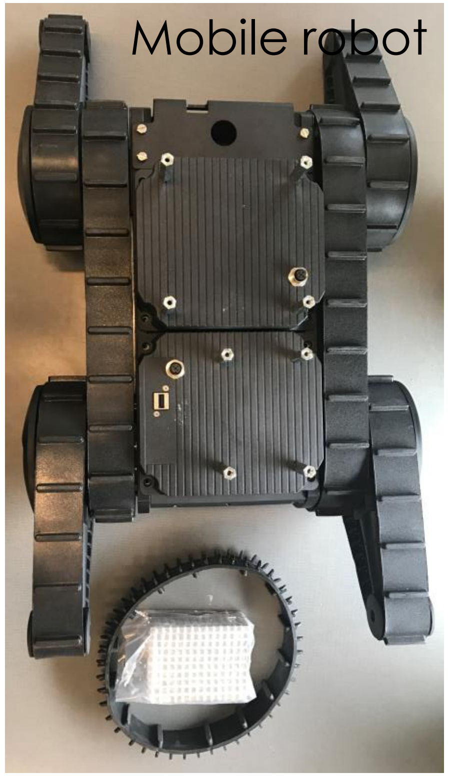



IHA FSW: 400 rpm, 70mm/min & 15kW IH

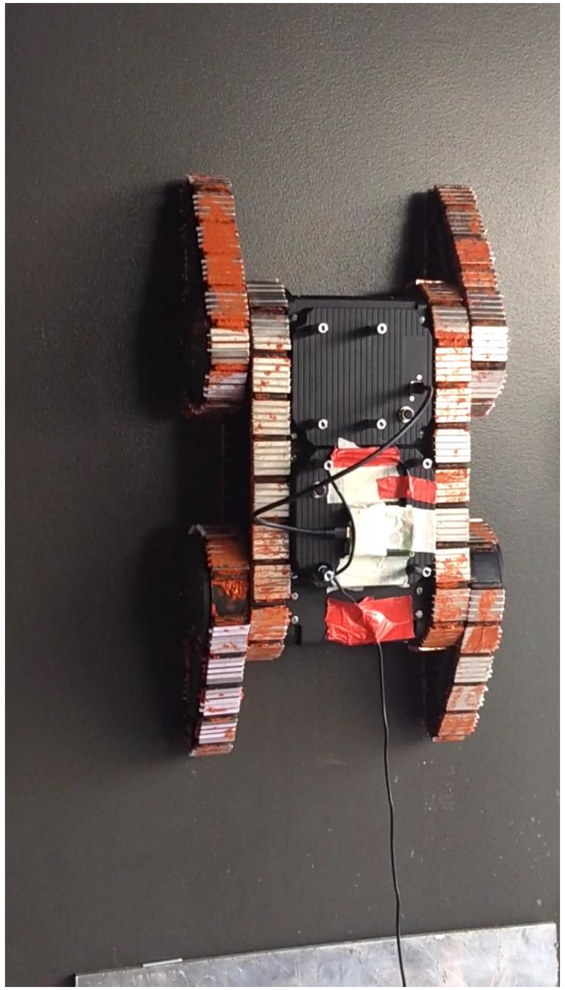
# Project Update: Robotic Platform

## Robot Retrofit for Vertical Navigation

- We modified a tracked mobile robot to include magnets on track surfaces to attach to a vertical metal surface.
- We tested the mobile robot on vertical testing walls.





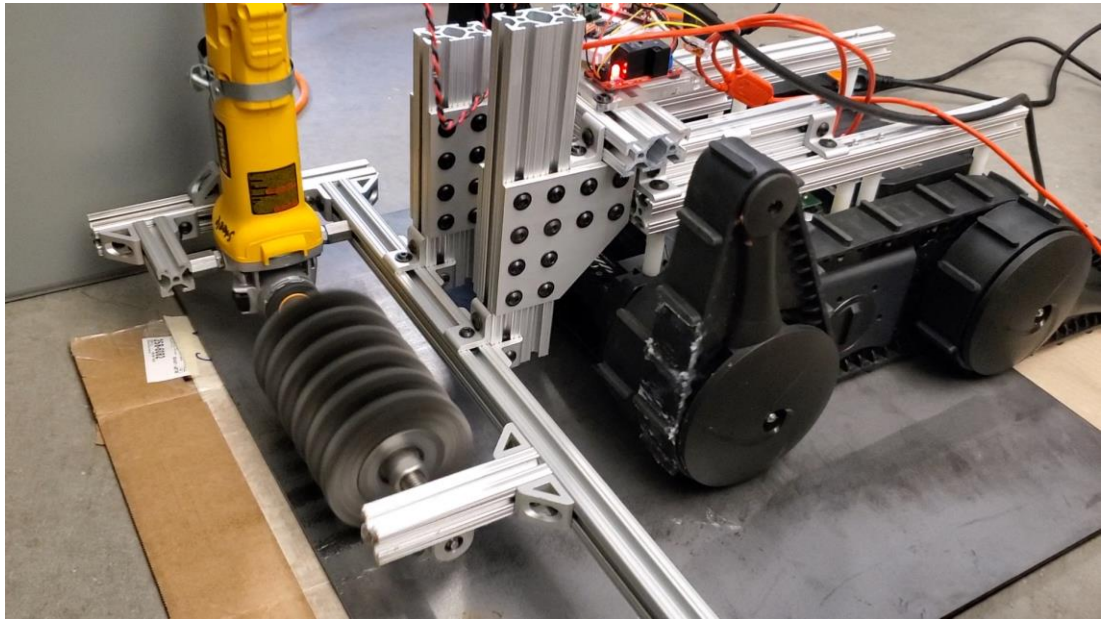
# Project Update: Robotic Platform

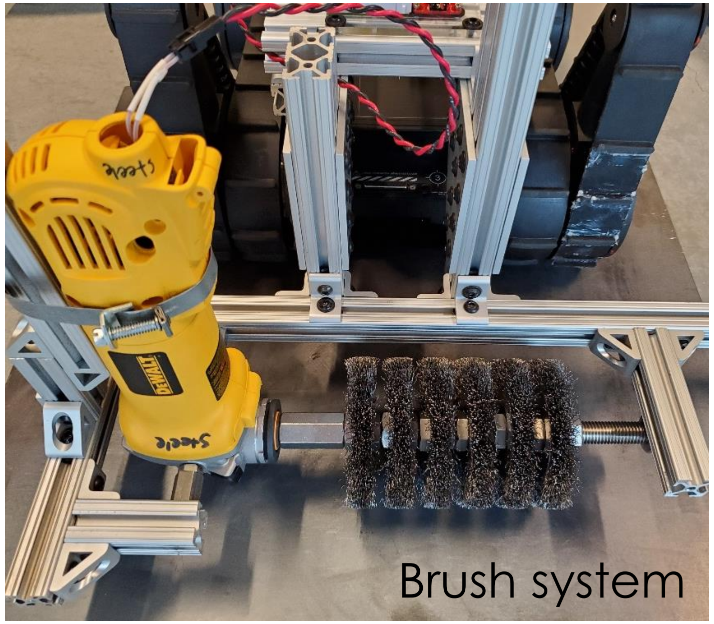
NATIONAL ENERGY TECHNOLOGY LABORATORY

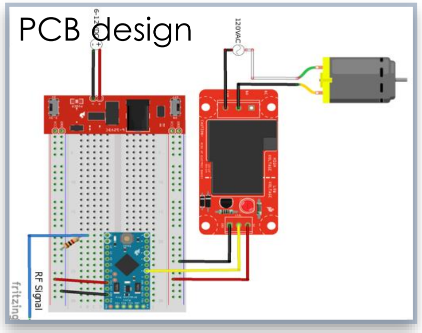
## Cleaning Mechanism Design

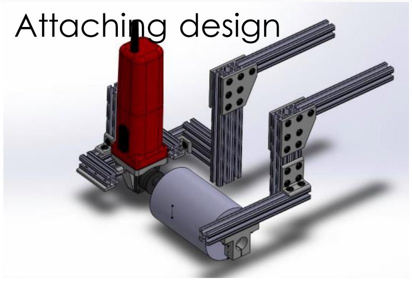
- We developed a brush cleaning mechanism for metal surface cleaning by modifying off-the-shelf cleaning tools.
- The cleaning tool was installed in the front of the robot to balance the weight of repair tools at the rear side.
- We tested the cleaning mechanism on steel plates.


Cleaning testing




Brush system

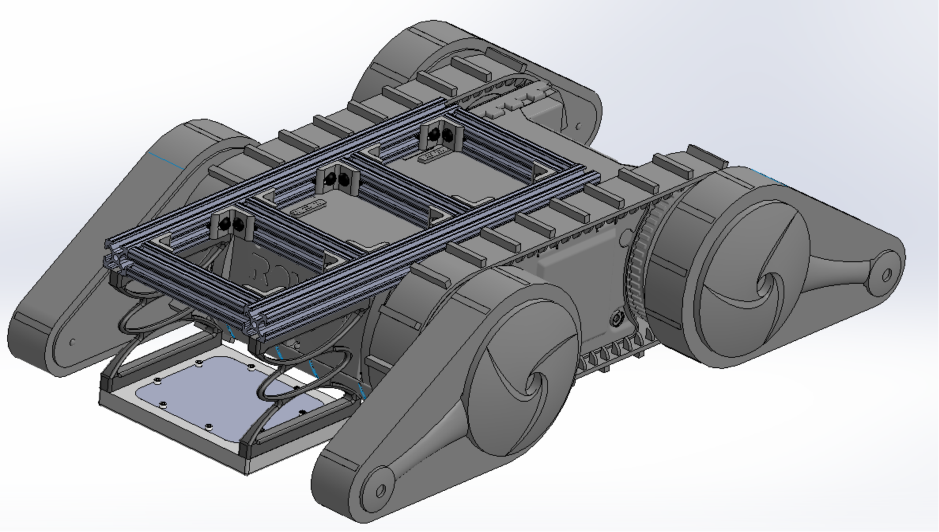

PCB design


Attaching design

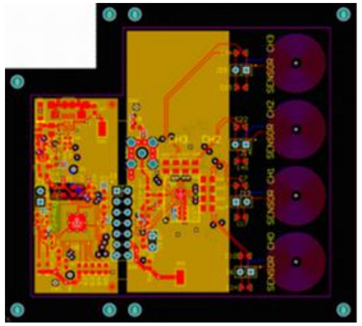
# Project Update: Robotic Platform

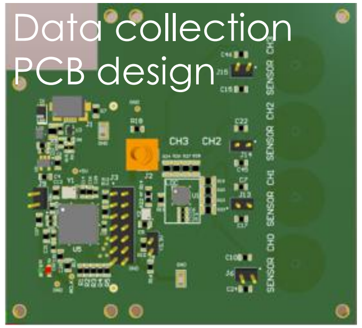
## NDE Sensor Integration

- We are integrating the NDE sensor with the mobile robot.
- The NDE sensor is installed in the front of the robot (between the cleaning tool and the robot body).
- We implemented a circular coil as the sensor prob and connect it with a signal processing PCB within a sensor enclosure for data collection.

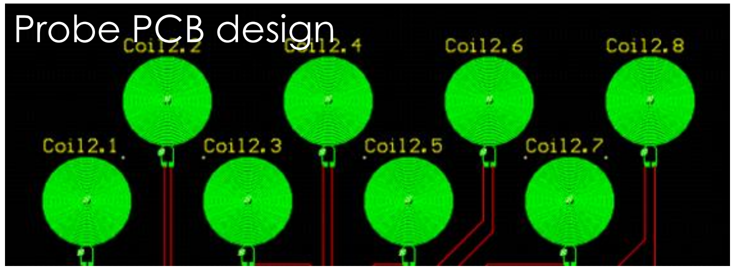


NDE sensor integration with the robot

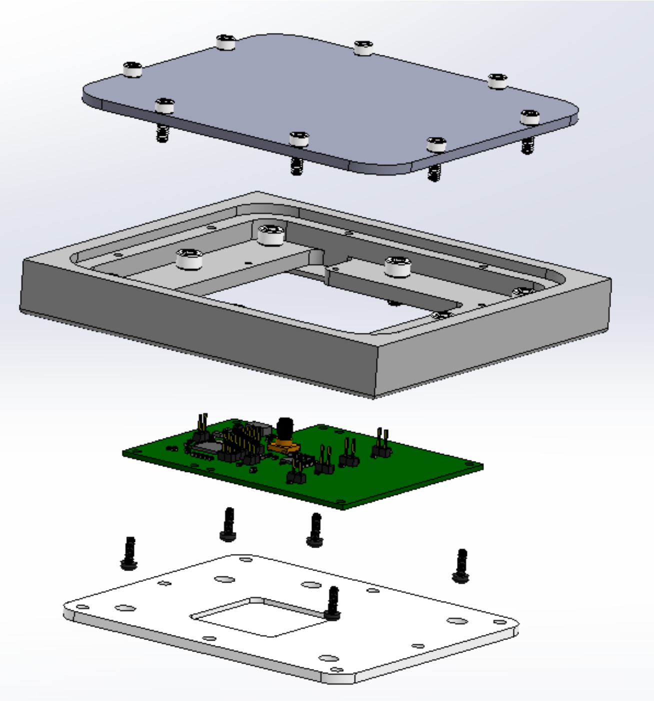




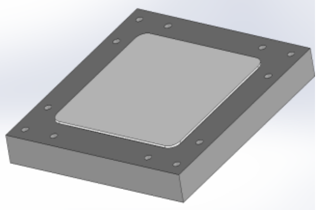
Data collection PCB design



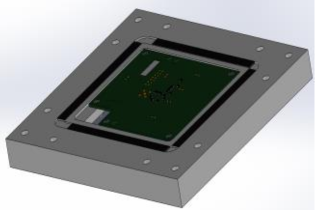

Probe PCB design



Sensor enclosure design



Top

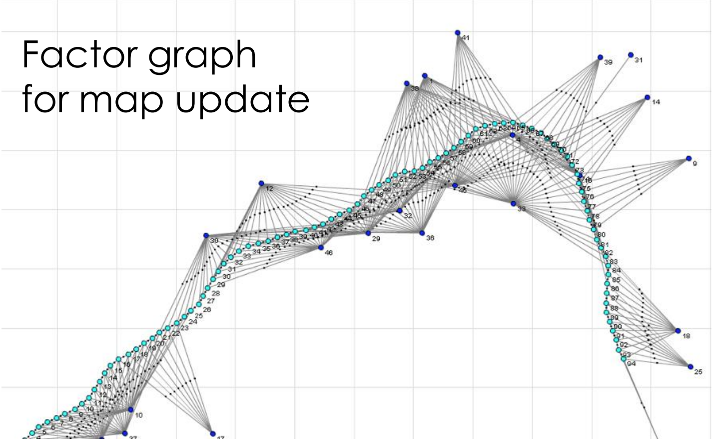


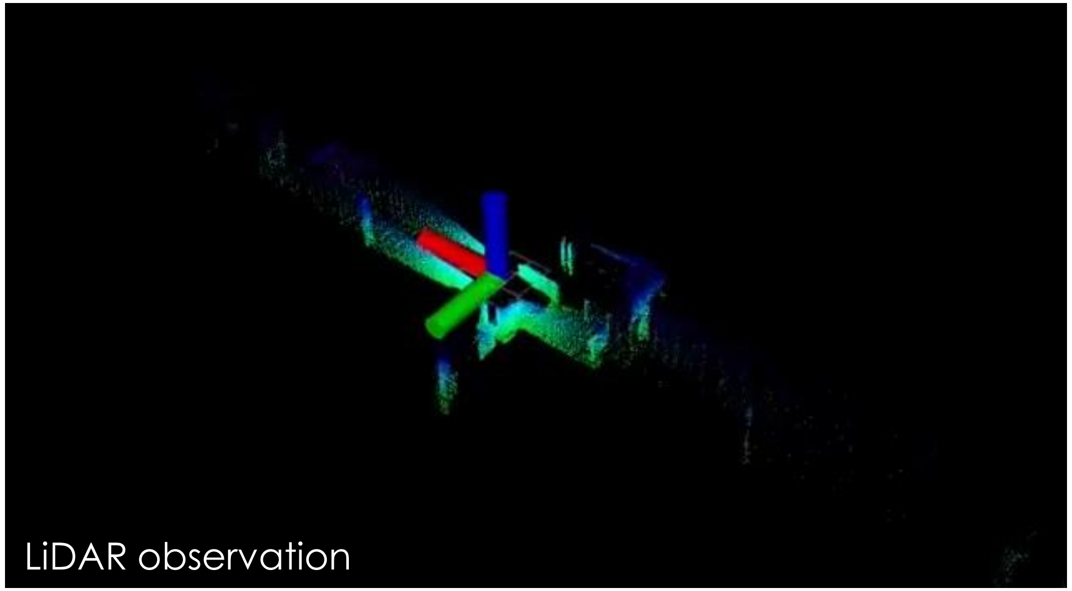
Bottom

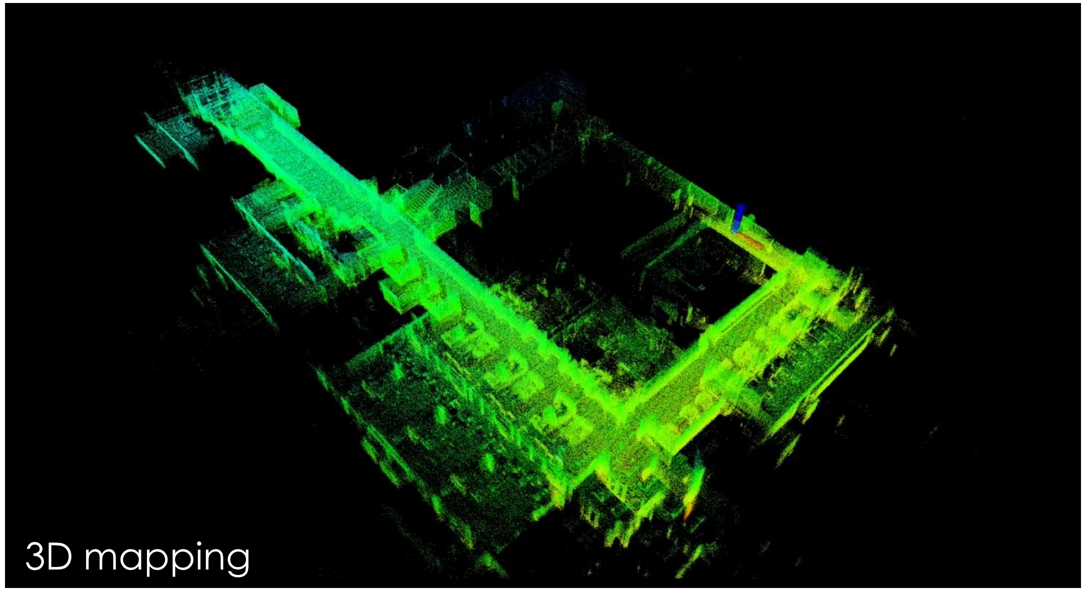
# Project Update: Artificial Intelligence

## 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 map is represented as a factor graph, and it is updated by graph updating.
- The method has been evaluated initially in dark, confined environments with sparse features.



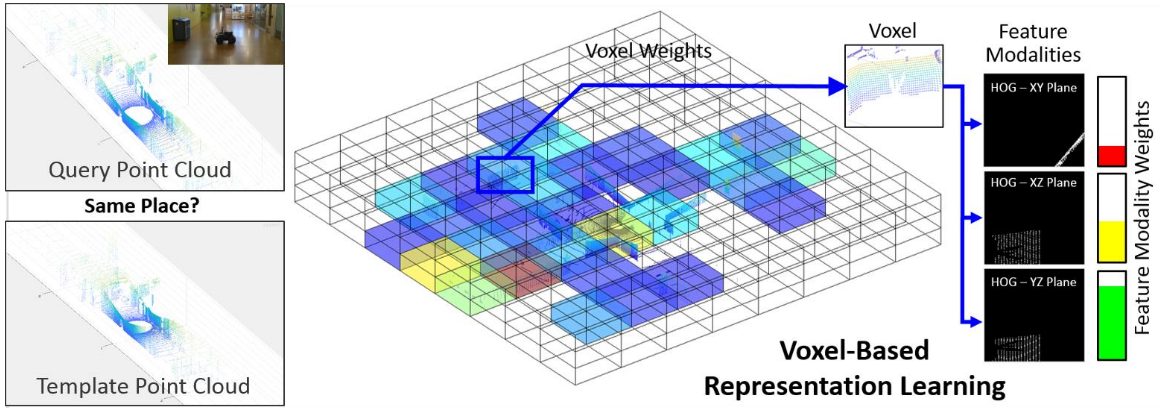



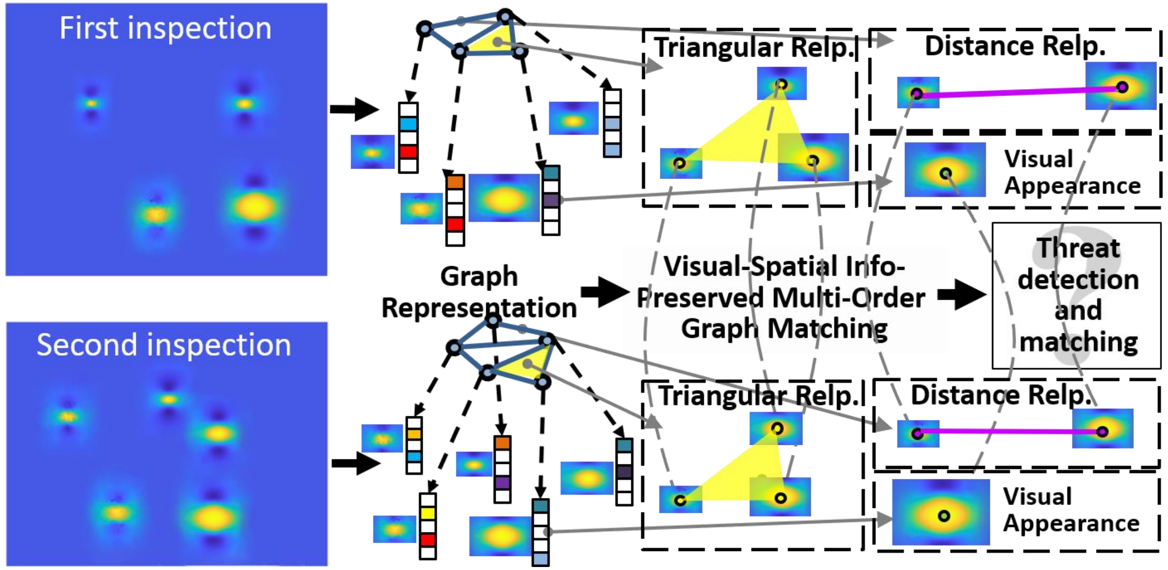



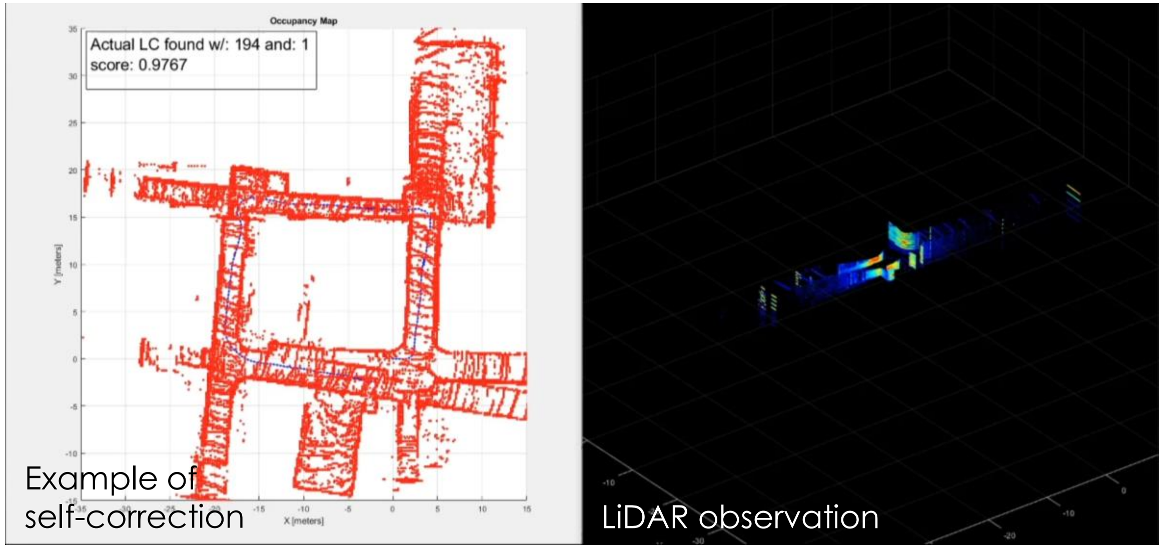
# Project Update: Artificial Intelligence

## Spatiotemporal Localization and 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.



# Project Update

NATIONAL ENERGY TECHNOLOGY LABORATORY

## Accomplishments

- Project accomplishments:
  - A portable NDE sensor has been designed that is being 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, which can be used when re-designing a portable repair tool for a robot platform.
  - AI algorithms have been developed for environment mapping, robot localization, and crack detection and tracking.
- Publication: Research from this project was published at VAMR'19, ENDE'19, ISEM'19, ICRA'20, VAMR'20, IROS'20.
  - *Best Poster Award:* Xiaodong Shi, Zachary Nahman, Fares Alharbi, Ciaron Hamilton, Yiming Deng, and Hao Zhang, "AI-enabled Robotic NDE for Structural Damage Diagnosis and Mapping", International Symposium on Applied Electromagnetics and Mechanics, 2019.
- Dr. Zhenzhen Yu and Dr. Hao Zhang were promoted to Associate Professor with tenure at Mines in 2020 spring.

# Preparing Project for Next Steps



## Research Challenges

- NDE data analysis requires real time or near real time signal processing ability to locate and characterize cracks for the repair assessment.
- Repair tool requires to be re-designed with a small size but having similar abilities in order to be installed on a robot.
- More data will be needed (e.g., obtained through simulation) to training AI and machine learning methods we are developing.
- Integrating the repair tool with the mobile robot is probably our biggest challenge, as both mechanical components and AI-based controls need to be integrated.
- Deploying an AI system with the complex robot platform (with perception sensors, NDE sensors, and repair tools) for smart autonomy is another big challenge.
- Pandemic!

# Preparing Project for Next Steps

## Market Benefits

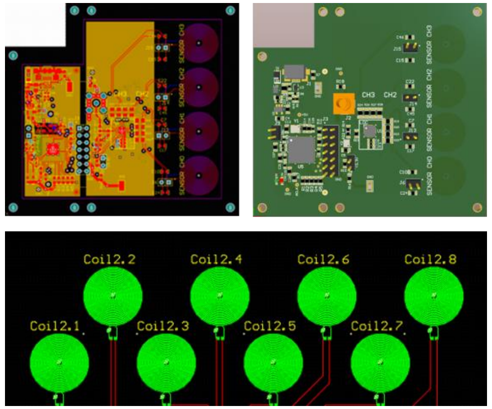
- Market benefits include limiting the need to send humans to difficult-to-access or hazardous areas, enabling automated inspection and repair, avoiding time consuming scaffolding, smartly collecting comprehensive and organized data.
- Impacts can be tremendous in terms of the time and cost savings,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

## Next Steps

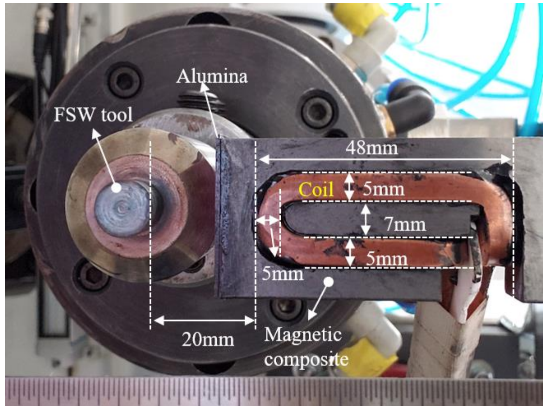
- Next steps for research mainly focus on integrating the repair tool onto the robot, and predictive damage analysis onboard a robot.
- We will also continue working on re-designing the repair tool from the perspective of robot integration.
- We will work with our industrial collaborators from *EnergynTech* and *Xcel Energy* to identify paths to market and conduct customer discovery.

# Concluding Remarks

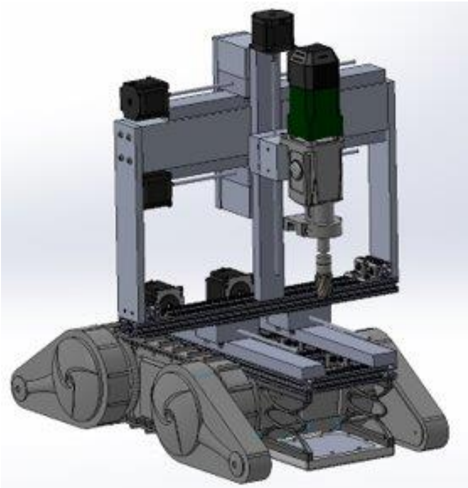
- Proposed Research: integrated **autonomous robots** that are equipped with NDE sensors to perform **real-time inspection**, operate repair devices to achieve **live repair**, and use **artificial intelligence** to enable smart data analysis and autonomy, in order to address cracks on boiler furnace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



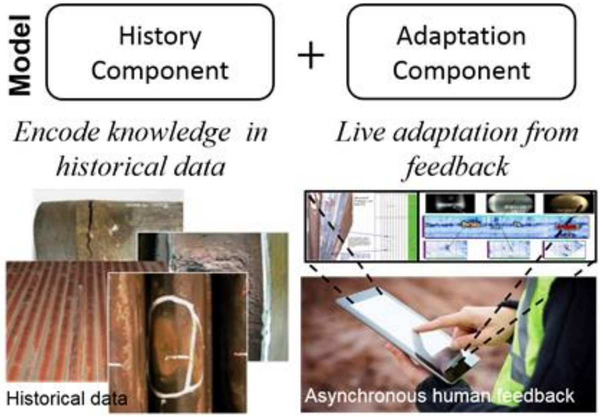

NDE Sensing and Assessment




Repair Device Design and Control



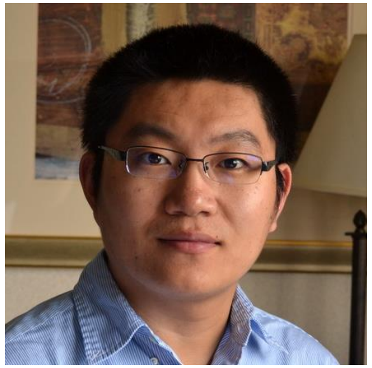
Robot Platform Integration




Artificial Intelligence

# Thank you!





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Andrew Petruska
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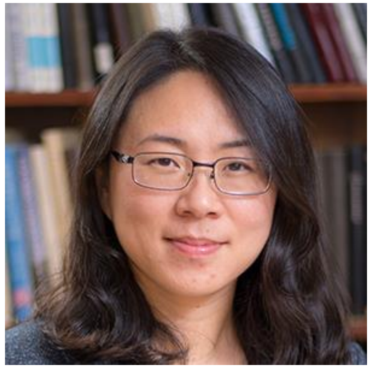

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