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

PIs: Hao Zhang[1], Yiming Deng[2], Steven Liu[1], Andrew Petruska[1], Lalita Udpa[2], and Zhenzhen Yu[1]
1. Colorado School of Mines 2. Michigan State University

PM: Anthony Zinn, National Energy Technology Laboratory

# Project Description and Objectives

## 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.

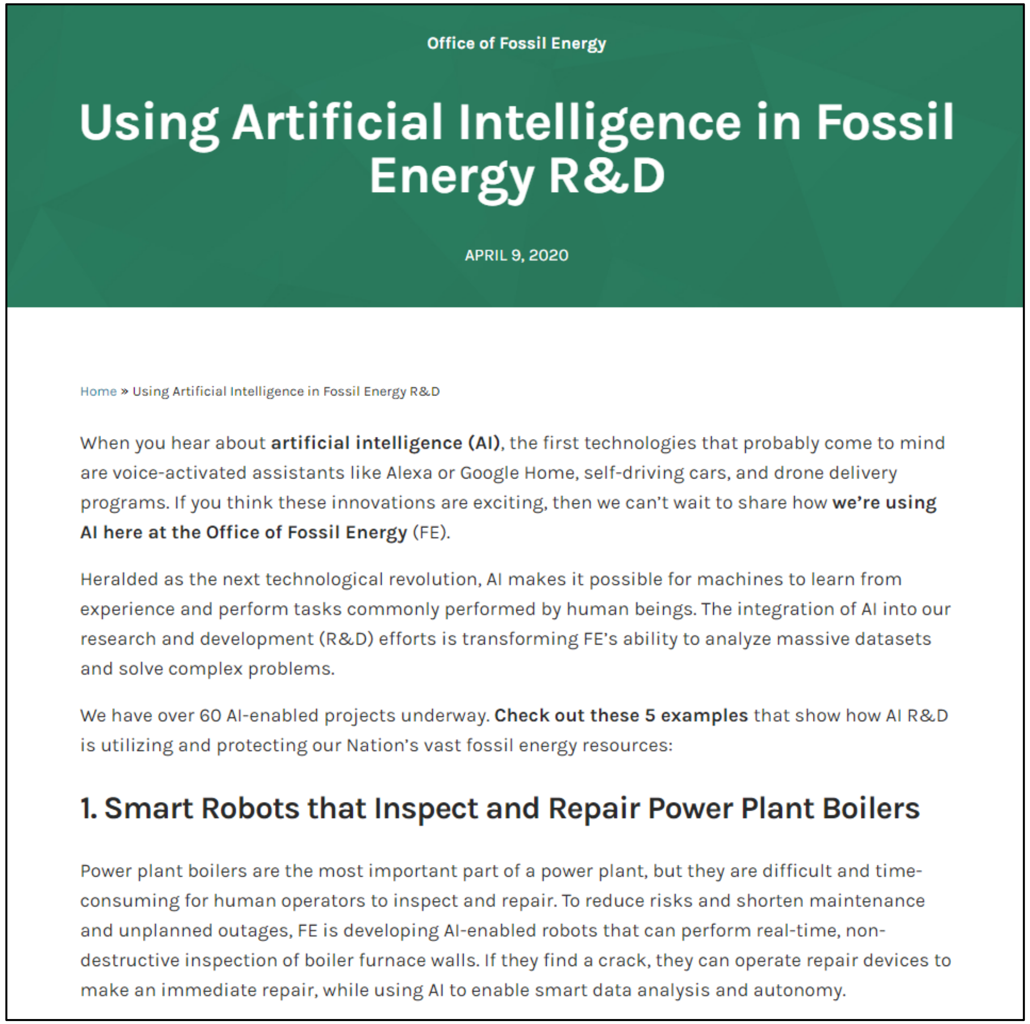
# Project Description and Objectives

## 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

## 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 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.

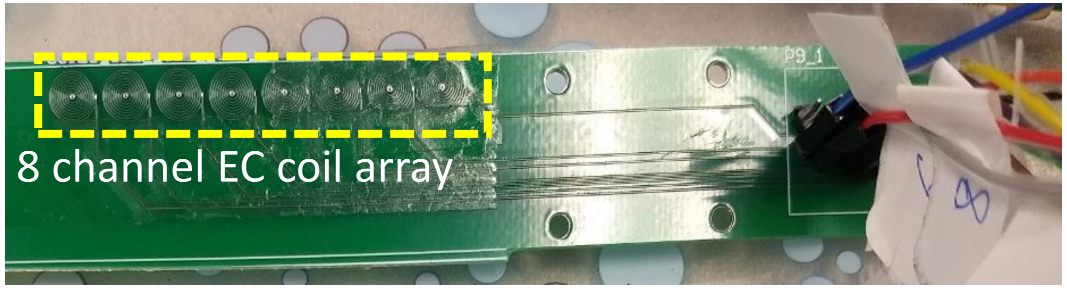
| Objectives | Lead | 2018 | 2019 | | | | 2020 | | | | 2021 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 |
| NDE Sensing and Assessment | Deng & Udpa (MSU) | NDE probe design | | | | Signal processing | | | | [redacted] | | | |
| 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 | | | [redacted] |
| Artificial Intelligence Development | Zhang (CSM) | 3D mapping and information fusion | | | | Spatiotemporal damage tracking | | | | Predictive damage analysis on robot | | | [redacted] |

Last review 05/13/2021

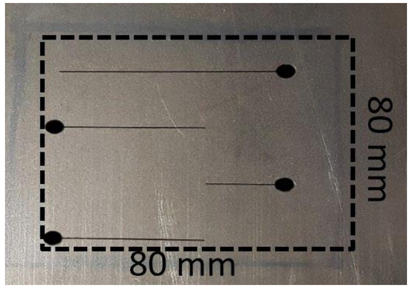
# Prior Achievements: NDE Sensor

## NDE Probe Design

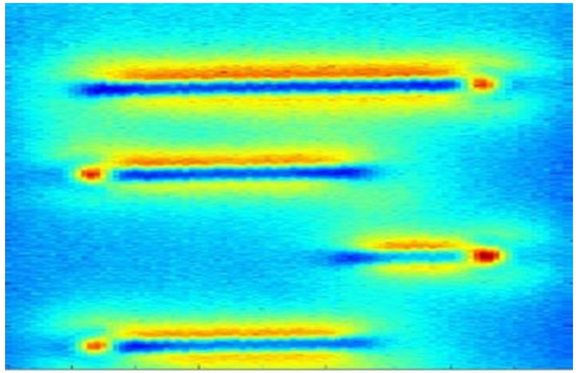
- An eddy current (EC)-based array sensor was designed which showed high scanning speed and detection accuracy.




Diameter of the coil is 0.5 (unit: cm)



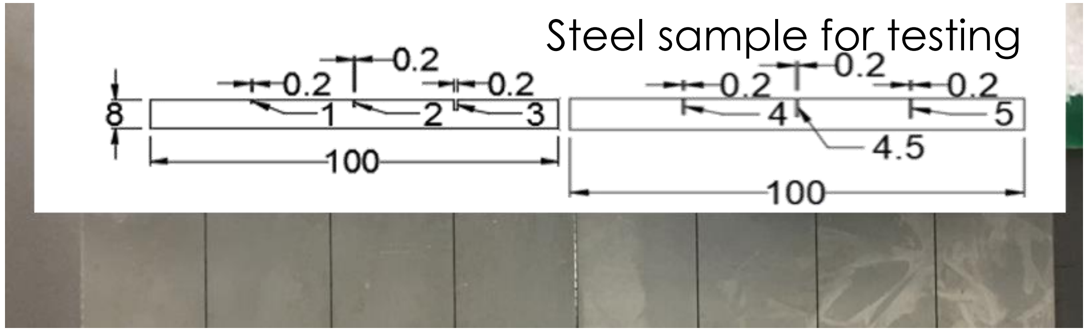

Steel Sample (A108): The width of the fabricated cracks is 200 μm and 400 μm

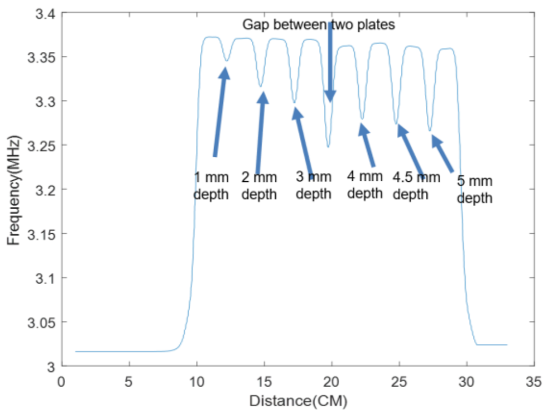


Data fusion scanning result

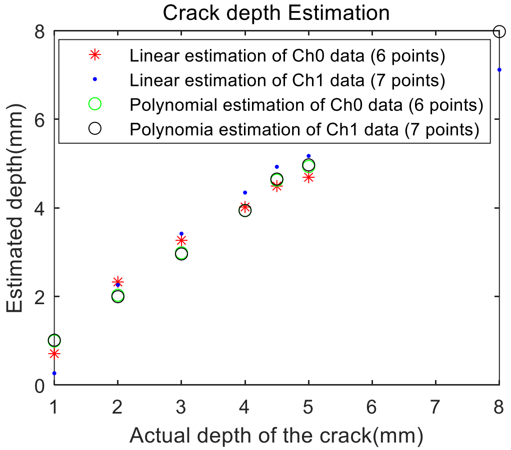
## NDE Signal Processing

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




Signal processing for crack detection



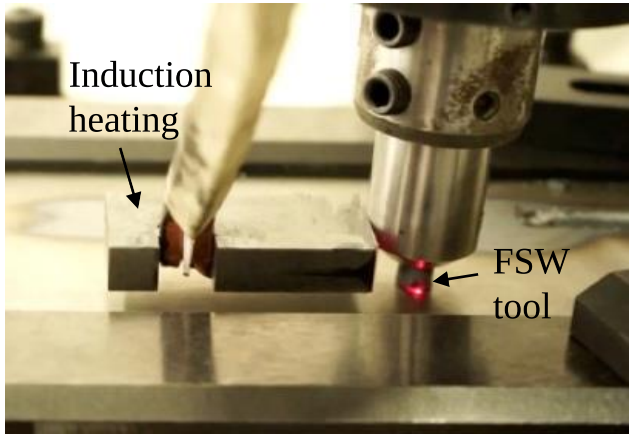

Signal processing for depth estimation

HUMAN-CENTERED ROBOTICS LAB

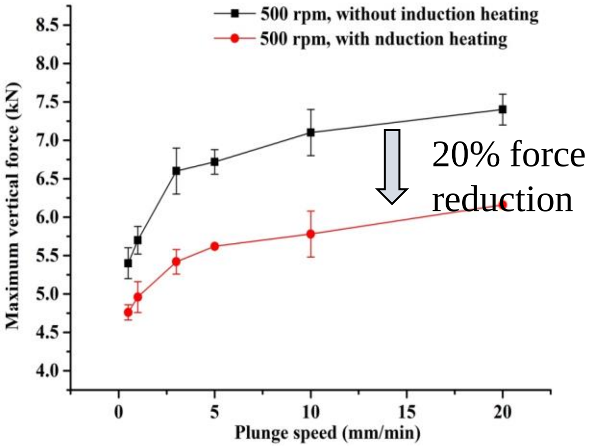
# Prior Achievements: Repair Tool

## 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%.



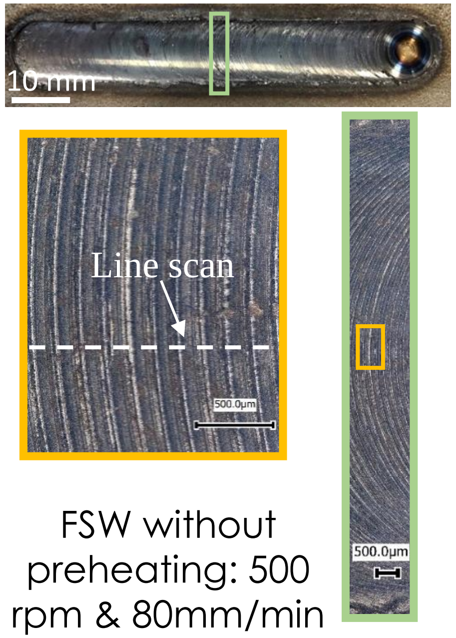

Side View of the IH-FSW repair tool



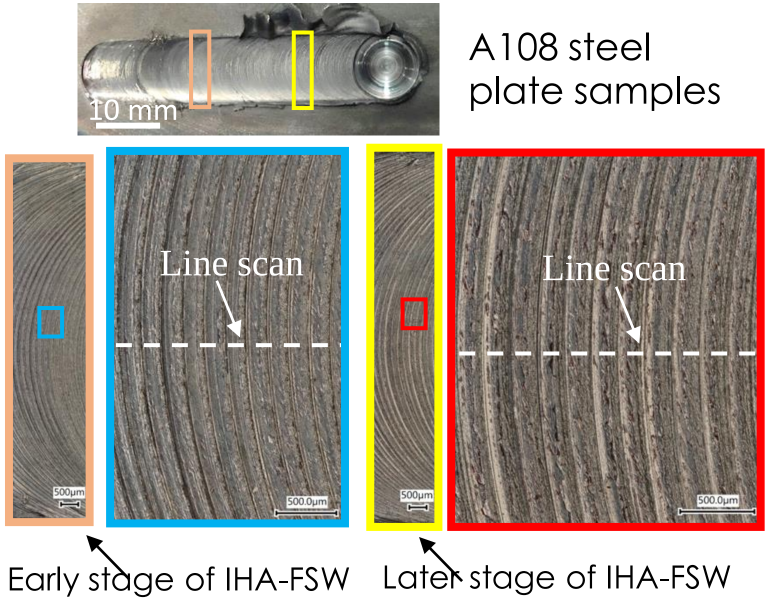

Effect of preheating

## 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.




FSW without preheating: 500 rpm & 80mm/min



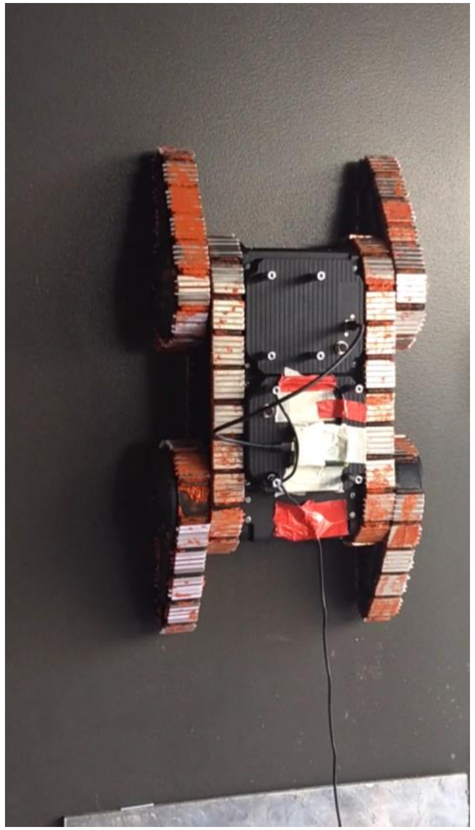

IHA FSW: 400 rpm, 70mm/min & an induction heating power of 15kW

HUMAN-CENTERED ROBOTICS LAB

# Prior Achievements: Robotic Platform

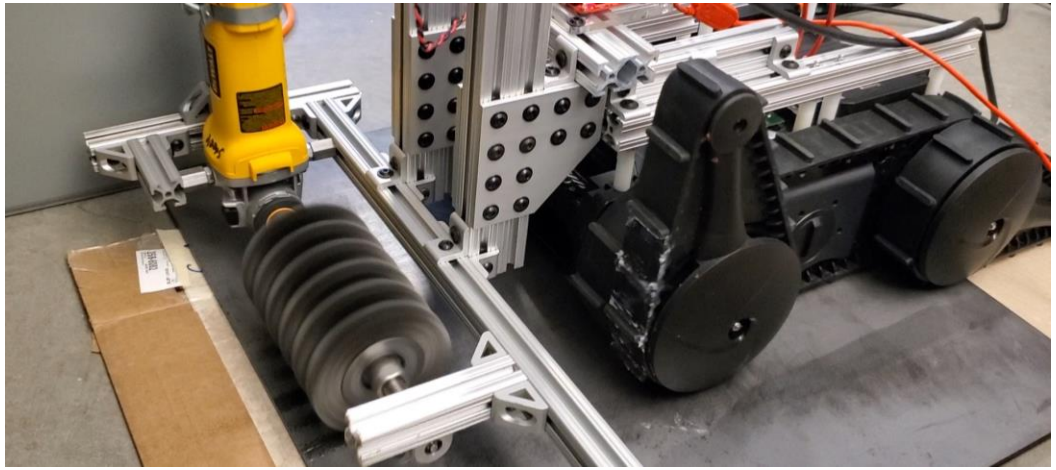
## Robot Retrofit for Vertical Navigation

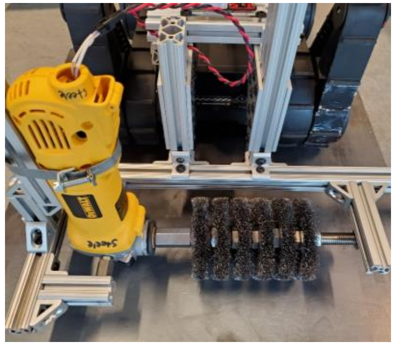
- We modified a tracked mobile robot to include magnets on track surfaces to attach to a vertical metal surface.

## Cleaning Tool Design

- We developed a brush cleaning mechanism for metal surface cleaning by modifying off-the-shelf cleaning tools.

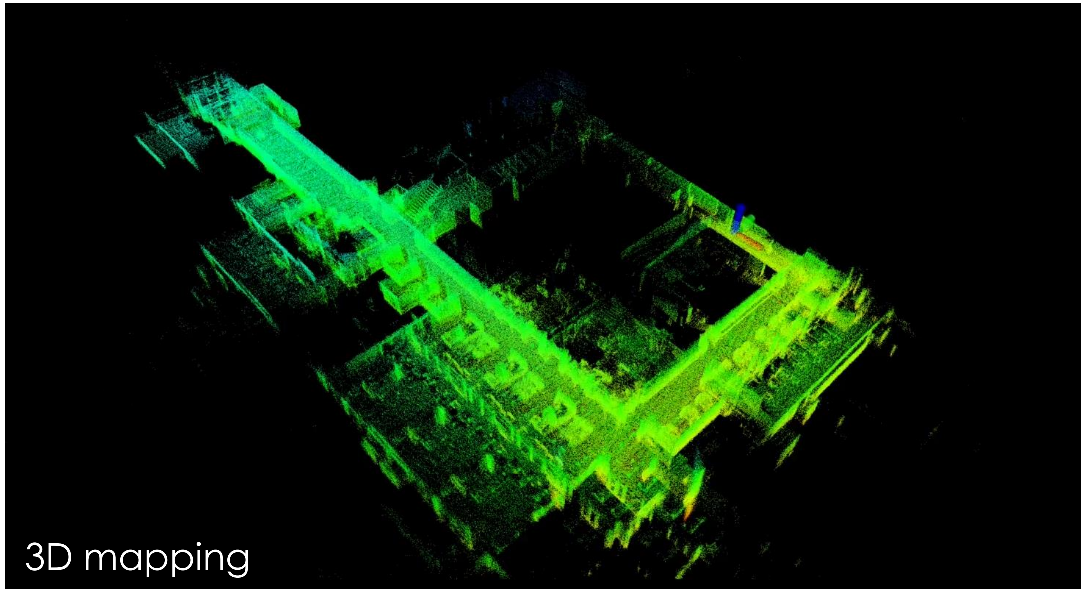




# Prior Achievements: Artificial Intel (AI)

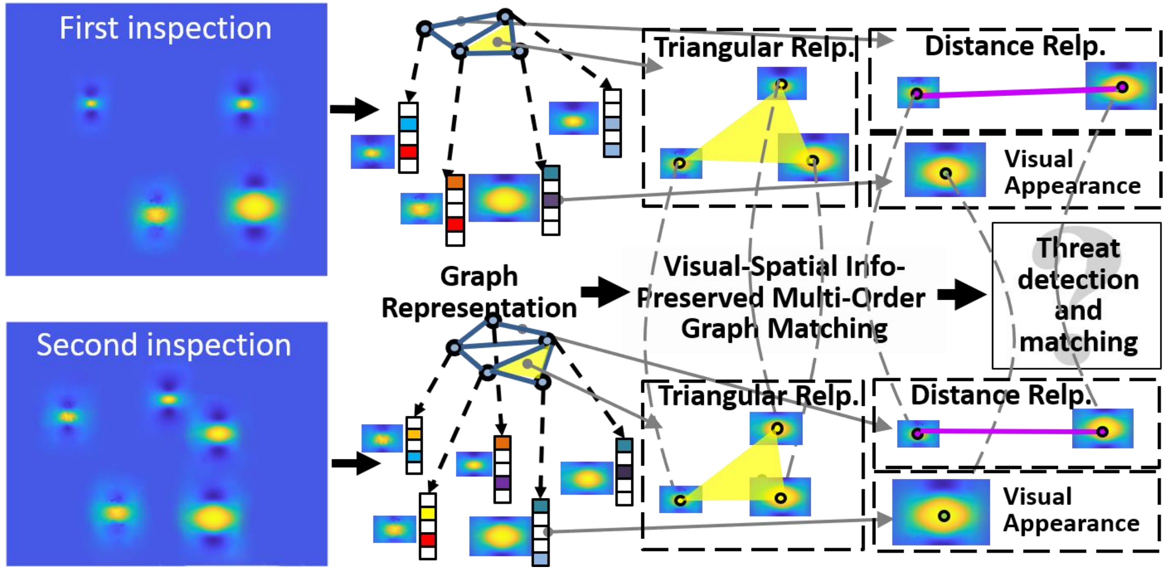
## 3D Mapping and Information Fusion

- 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.

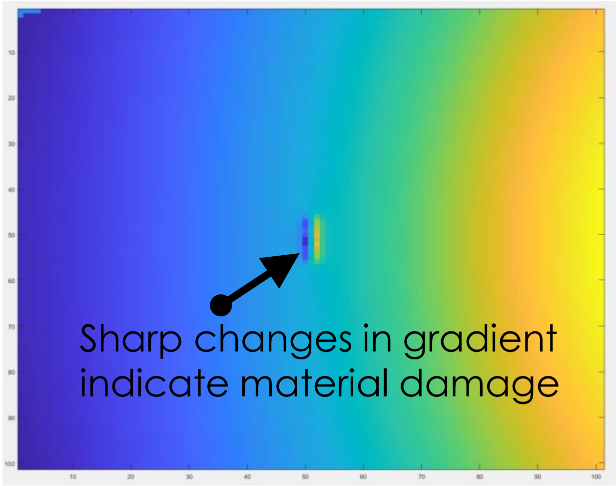



HUMAN-CENTERED ROBOTICS LAB

# Project Update: NDE Integration

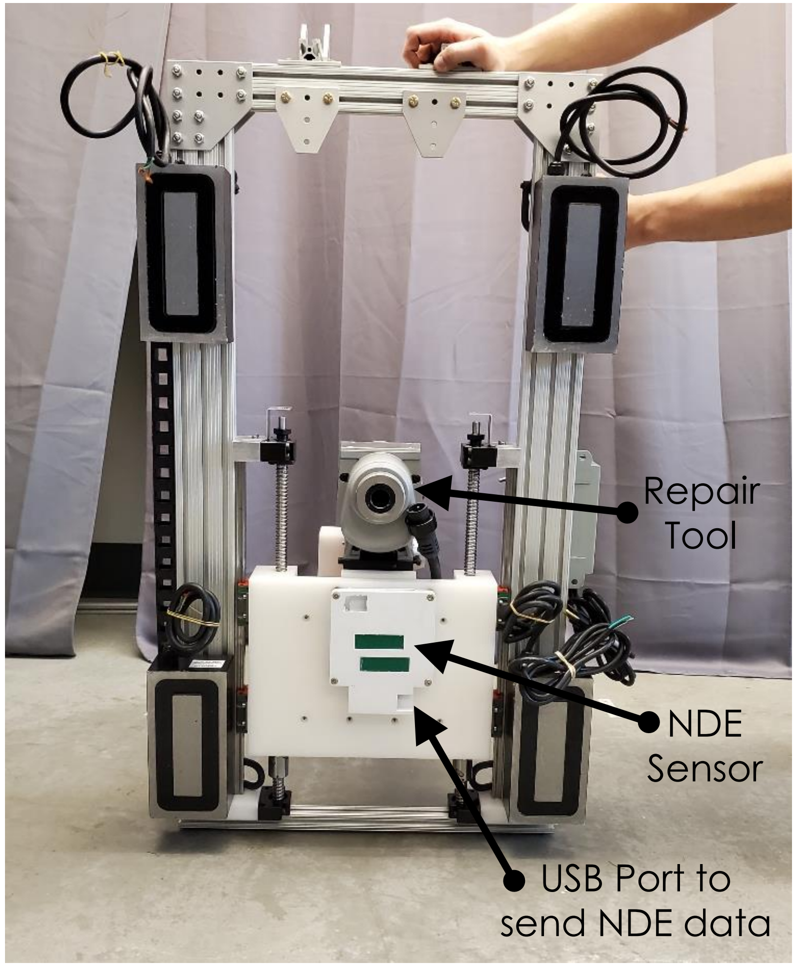
## NDE Sensor Integration

- 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 bya magnetic tracked robotic platform.
- This design allows us to obtain accurate positioning data for precise scan localization and repair.




Scan Image Reconstruction

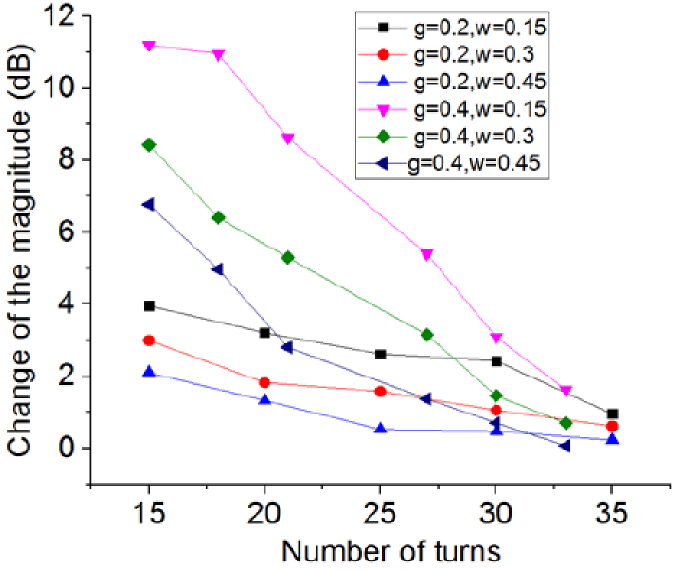

Robotic Platform

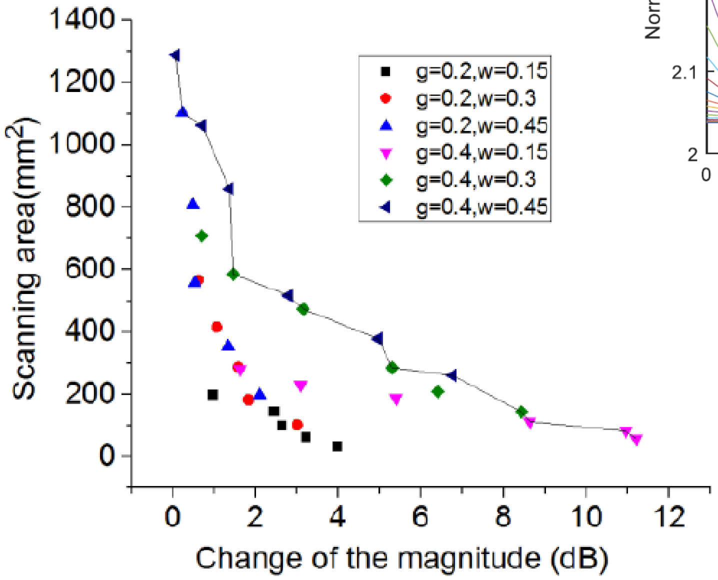


# Project Update: NDE Integration

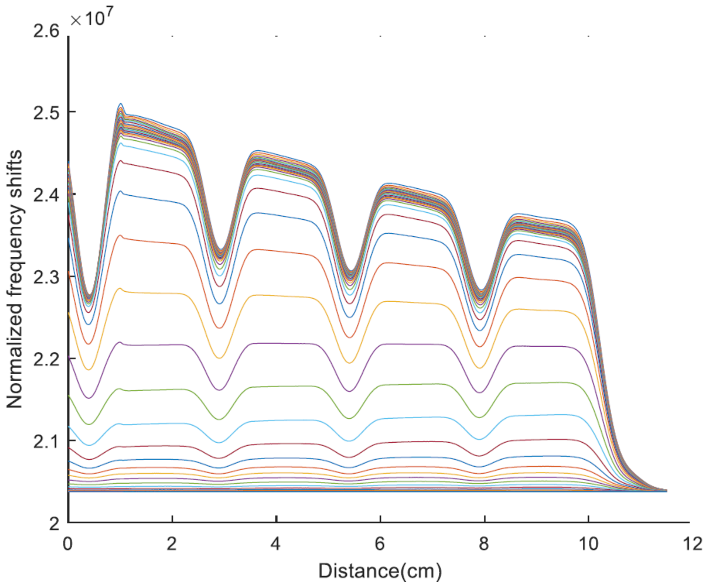
## NDE Sensing Evaluation

- 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

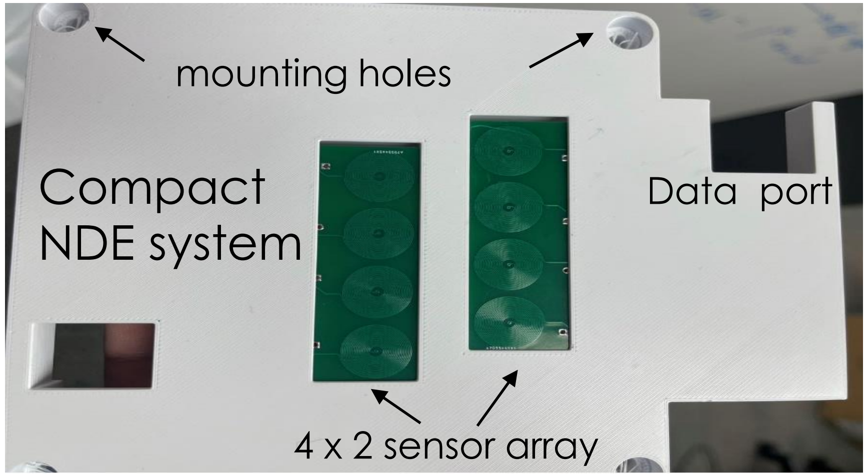



The magnitudes change at the resonating frequency and the Pareto front of maximizing the scanning area and the sensitivity of the sensor.



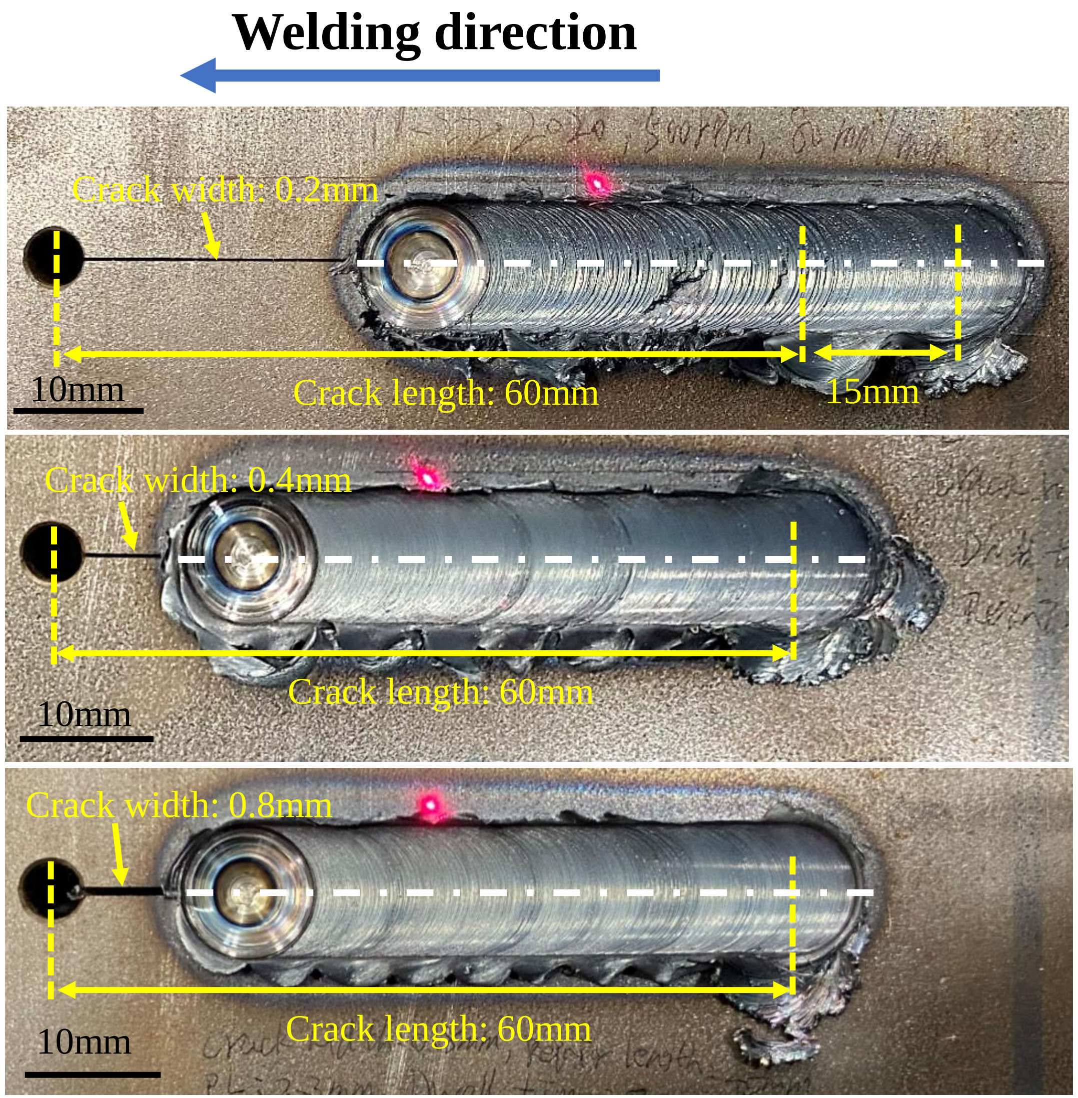

Normalized frequency shifts with different lift-off distance of the eddy current sensor shows good scanning ability of the sensor



# Project Update: Repair Integration

## 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.



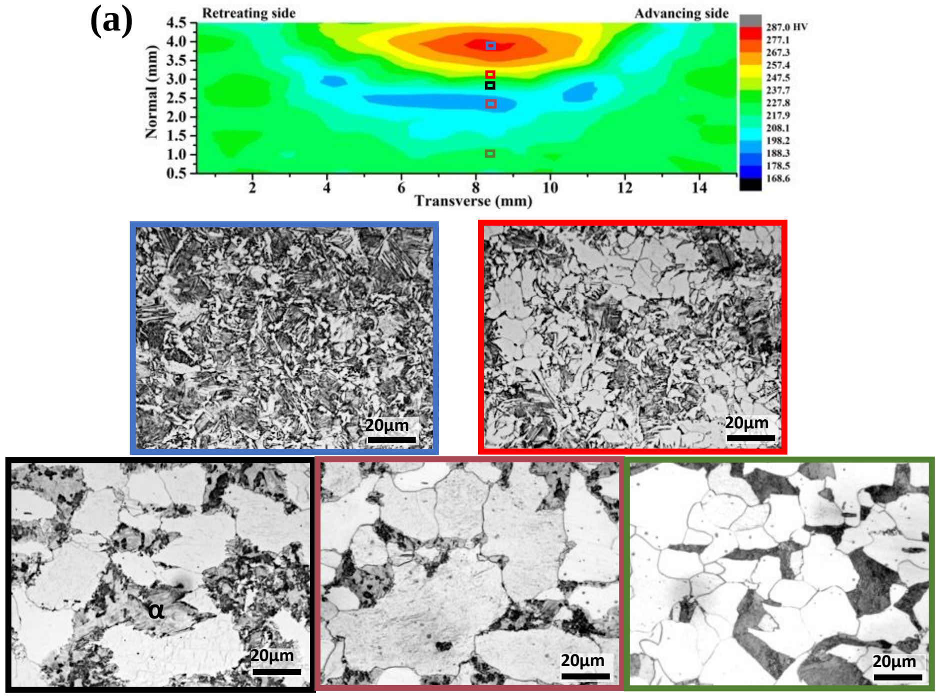

HUMAN-CENTERED ROBOTICS LAB

# Project Update: Repair Integration

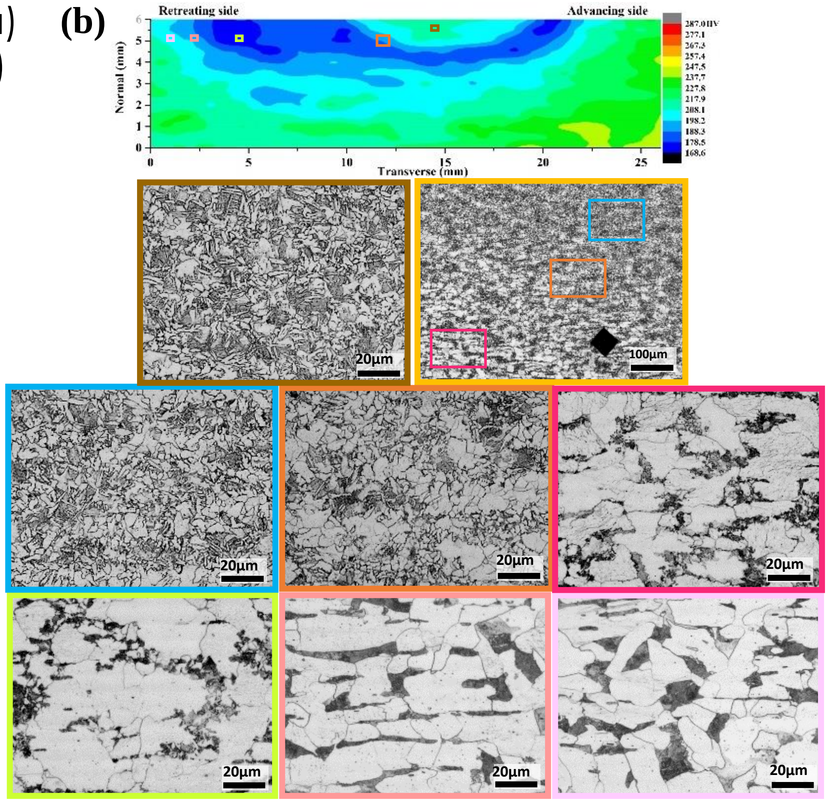
## Metallurgical Characterization after Repair Evaluation

- 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

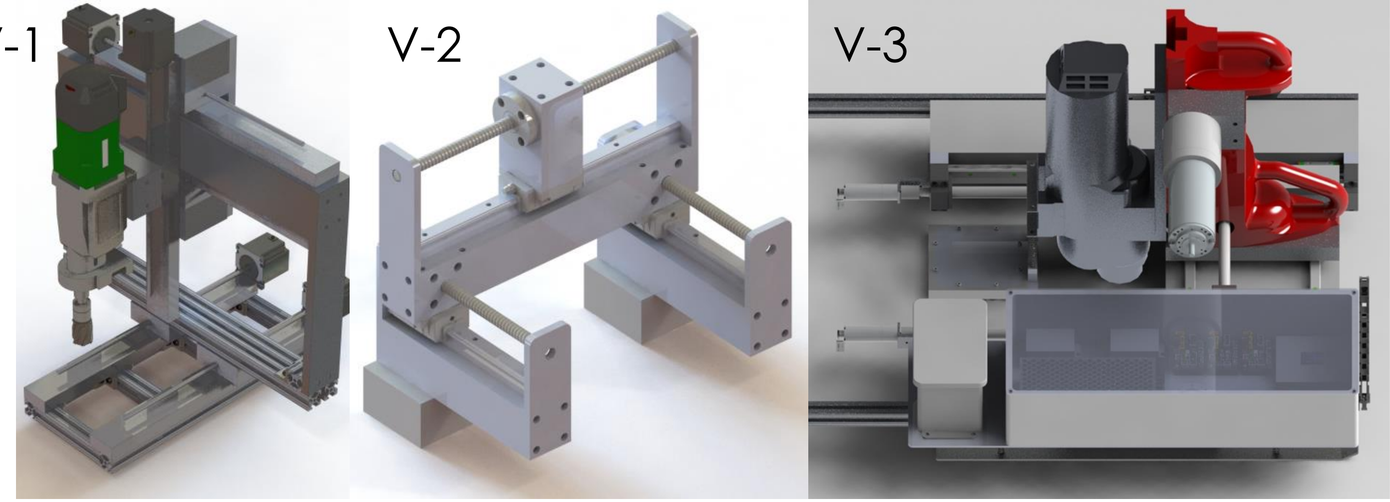



IHA FSW: 400 rpm, 70mm/min & 15kW IH

# Project Update: Repair Integration

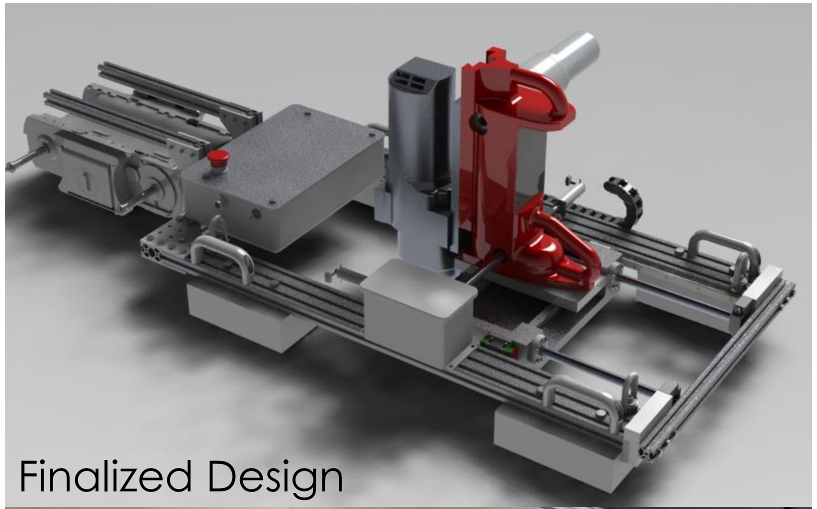
## Progress on Repair Tool Integration

- 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



V-1 V-2 V-3

Previous Iterations of Platform Design



Finalized Design

HUMAN-CENTERED ROBOTICS LAB

# Project Update: Artificial Intelligence

## Machine Learning for Crack Recognition

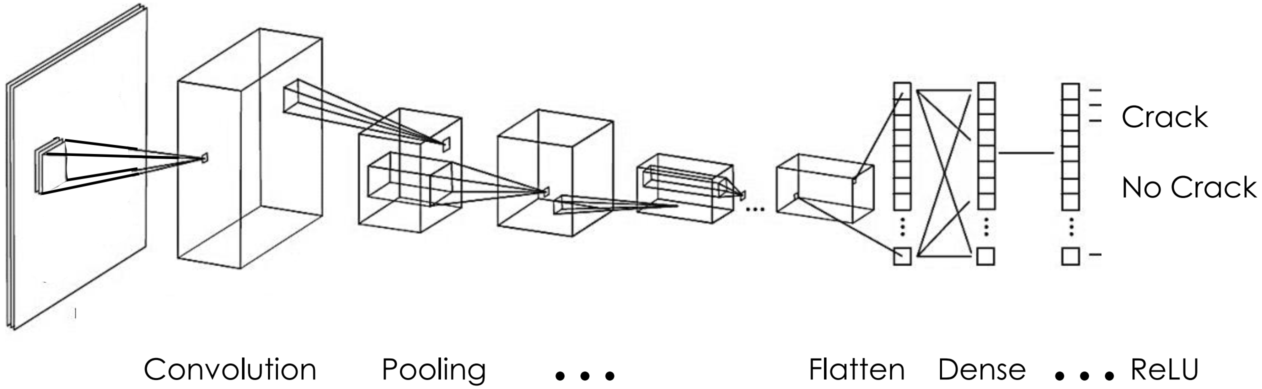
### Ridge Classifier

- 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
  - $min_w \|y^T - w^T x\|_2^2 + \alpha \|w\|_2^2$
    - $x = feature\ vector$
    - $w = learned\ weight\ matrix$
    - $y = observations$
    - $\alpha = regularization\ hyperparameter$
    - 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

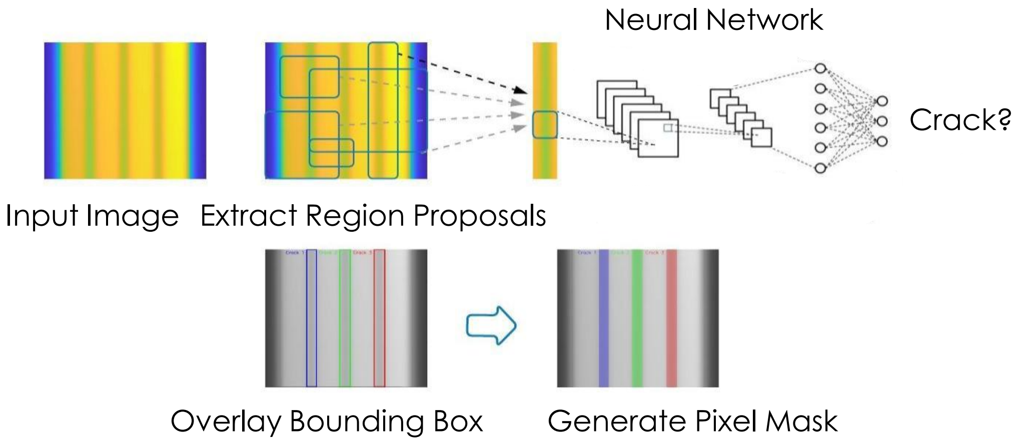


# Project Update: Artificial Intelligence

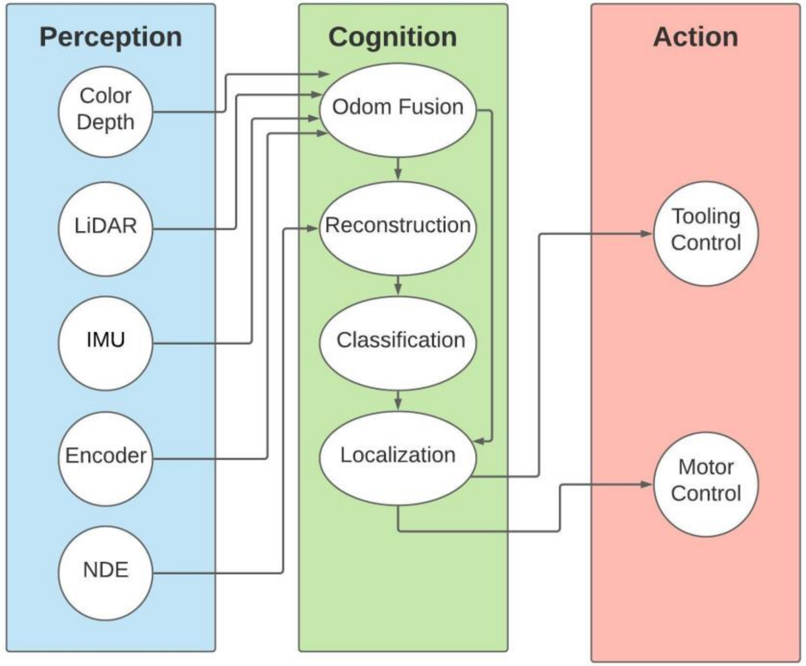
## Software System Integration

- 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

# Project Update

## 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.
  - *2019-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", Int'l Symposium on Applied Electromagnetics and Mechanics, 2019.
  - *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

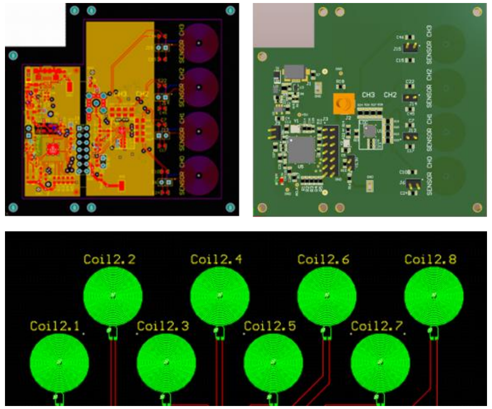
- Market benefits include limiting the need to send humans to difficult-to-access or hazardous areas, enabling automated inspection and repair, avoiding time consuming scaffolding, smartly collecting comprehensive and organized data.
- Impacts can be tremendous in terms of the time and cost savings,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

## Next Steps

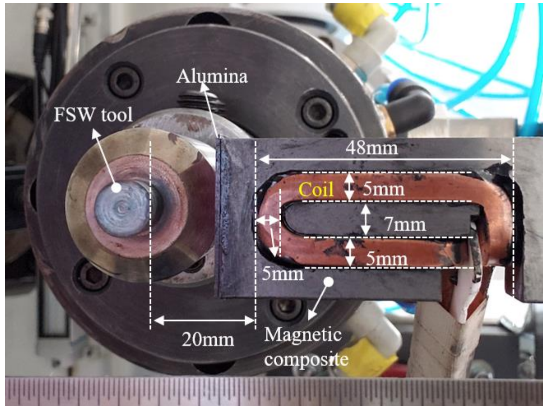
- More data will be needed (e.g., obtained through simulation) to training AI and machine learning methods we are developing.
- Integrating an AI software system with the complex robot platform (with perception sensors, NDE sensors, repair tools, and two onboard embedded computers) for smart autonomy 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 costumer discovery.

# Concluding Remarks

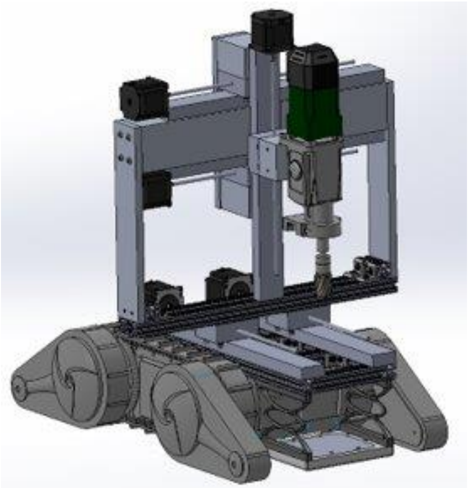
- Proposed Research: integrated **autonomous robots** that are equipped with NDE sensors to perform **real-time inspection**, operate repair devices to achieve **live repair**, and use **artificial intelligence** to enable smart data analysis and autonomy, in order to address cracks on boiler furnace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



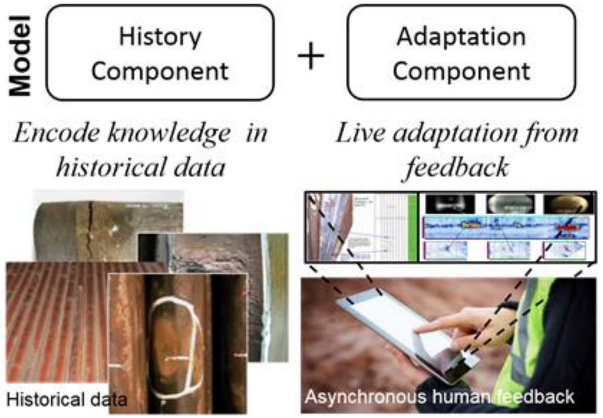

NDE Sensing and Assessment




Repair Device Design and Control



Robot Platform Integration



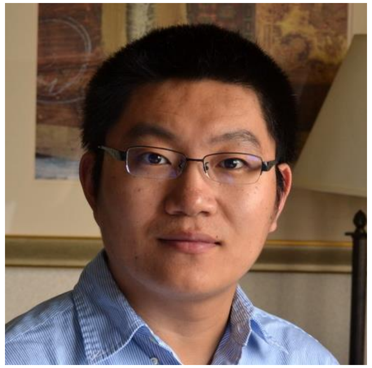

Artificial Intelligence

# Acknowledgment and Disclaimer


- This material is based upon work supported by the Department of Energy Award Number DE-FE0031650.

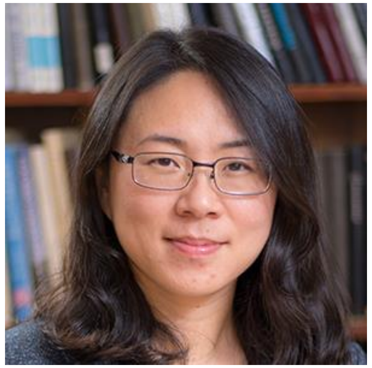
- This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

# Thank you!



Hao Zhang
@ Mines

Andrew Petruska
@ Mines



Zhenzhen Yu
@ Mines

Steven Liu
@ Mines

Yiming Deng
@ MSU

Lalita Udpa
@ MSU

Students:

Lucas Utke

Anthony Olvera

Erzhuo Gao

Xiaodong Shi

- We thank our *Xcel Energy* and *EnergynTech* collaborators for making us a stronger team.
- We thank our PM Anthony Zinn for great discussions with us on the project.