# 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

# Project Description and Objectives

## Background

- Boiler inspection and repair is one of the main focuses during power plant overhauls.
- Boiler failures can:
  - cause loss of life and safety issues
  - cost hundreds of thousands of dollars in equipment repairs, property damage, and production losses
  - drive up the cost of electric power
- Failures can be prevented by performing regular maintenance.

The coal-fired Hayden generating station in Colorado

# Introduction

## Challenges

- Boiler maintenance is challenging and dangerous on scaffolding in the confined space inside a boiler.
- The operation is time-consuming due to the large area of vertical structures and tremendous effort needed for scaffolding.
- E.g.: maintaining 50,000 ft2 of furnace walls (water walls) during a single overhaul takes two weeks to complete, while scaffolding itself costs $100,000.

Hayden Unit 1 scaffolding for manual inspection and repair

# 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.

| 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. |

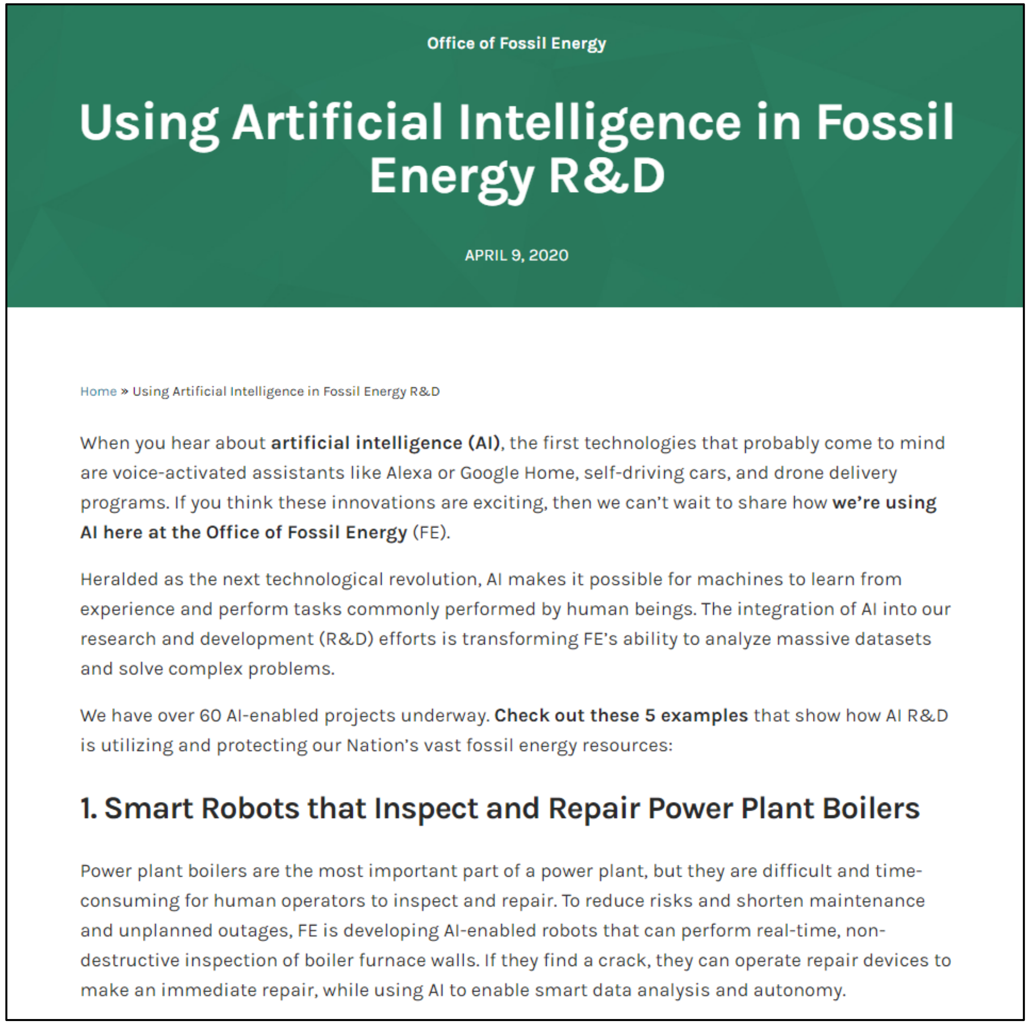
# Project Description and Objectives

## Strategic Alignment to FE Objectives

- This project well 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.

"Fossil Energy Roadmap," United States Department of Energy (DOE), 2020.

# 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.

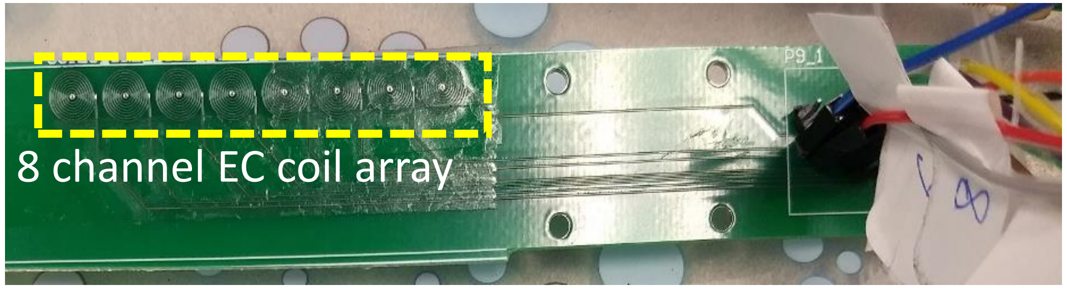
| Objectives | Lead | 2018 | 2019 | | | | 2020 | | | | 2021 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 |
| NDE Sensing and Assessment | Deng & Udpa (MSU) | NDE probe design | | | | Signal processing | | | | [redacted] | | | |
| 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

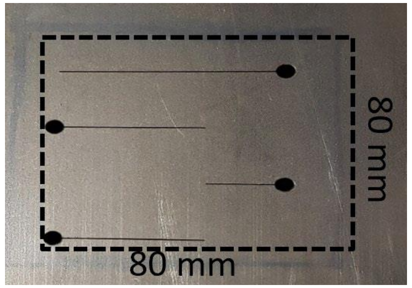
# Project Achievements: NDE Sensor

## NDE Probe Design (Task 1.1)

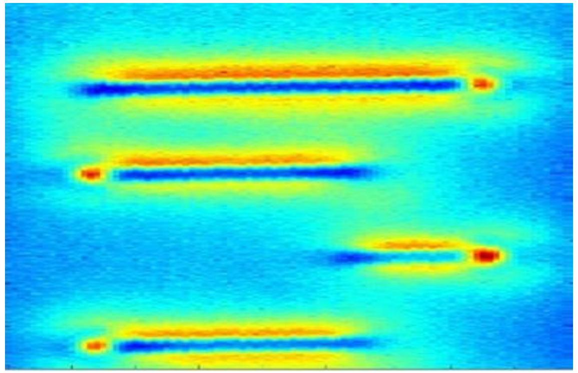
- An eddy current (EC)-based sensor array was designed which showed high scanning speed and detection accuracy.




Diameter of the coil is 0.5 (unit: cm)



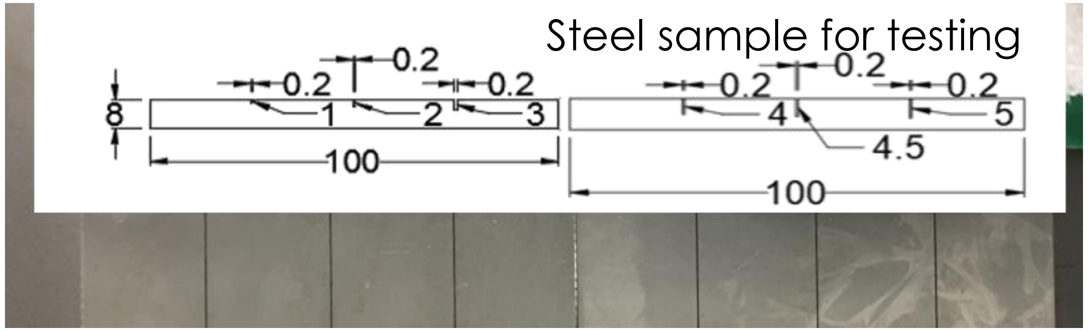

Steel Sample (A108): The width of the fabricated cracks is 200 μm and 400 μm

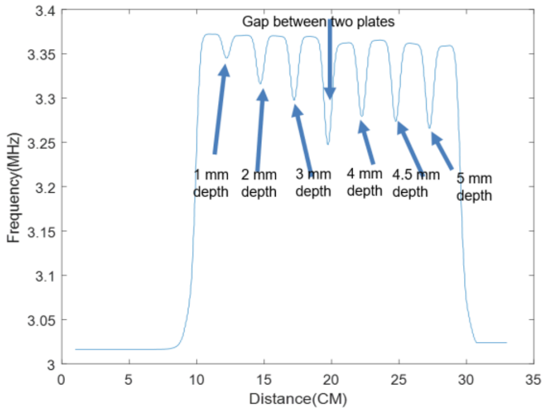


Sensor array scanning result

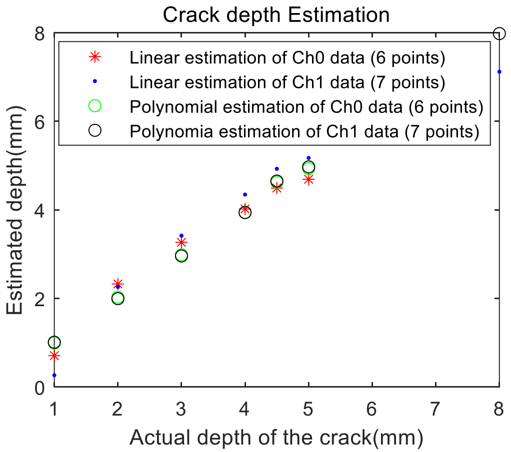
## NDE Signal Processing (Task 1.2)

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




Signal processing for crack detection



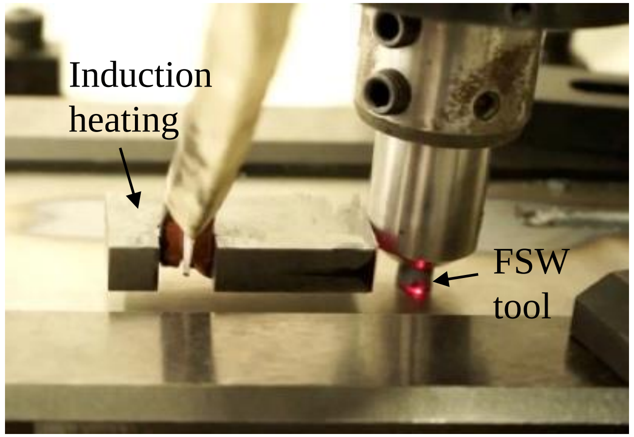

Signal processing for depth estimation

HUMAN-CENTERED ROBOTICS LAB

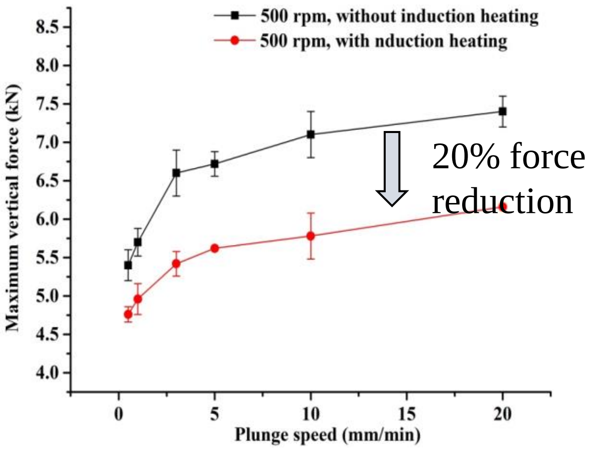
# Project Achievements: Repair Tool

## IHA-FSW Repair Tool (Task 2.1)

- 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%.



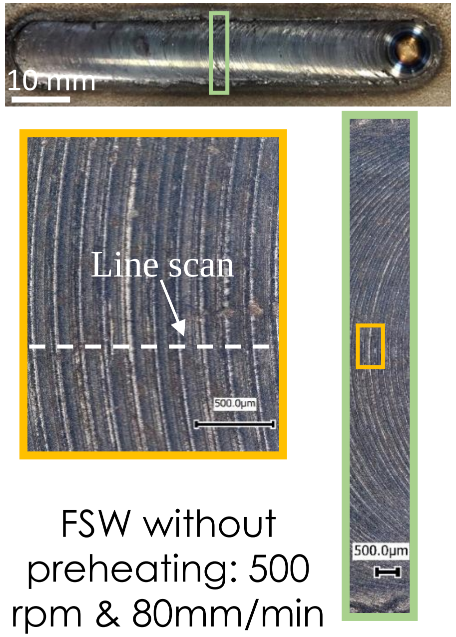

Side View of the IH-FSW repair tool



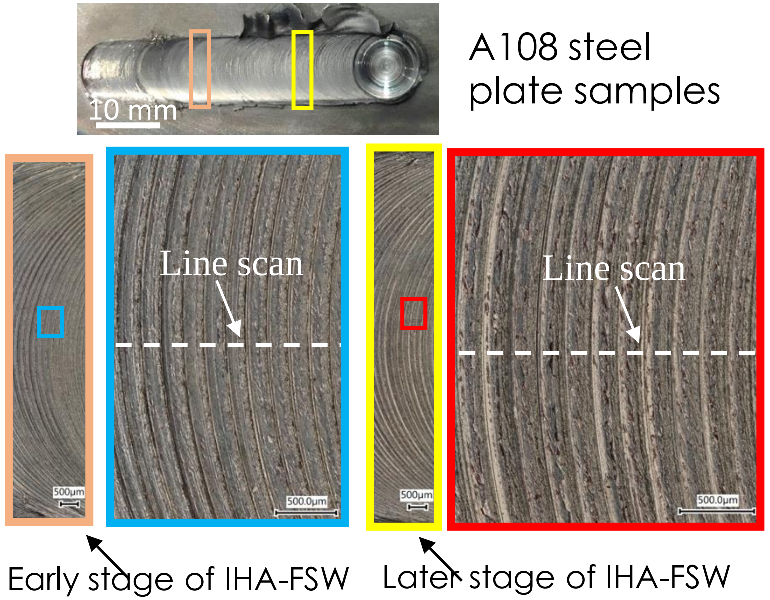

Effect of preheating

## Repair Protocol (Task 2.2)

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




FSW without preheating: 500 rpm & 80mm/min

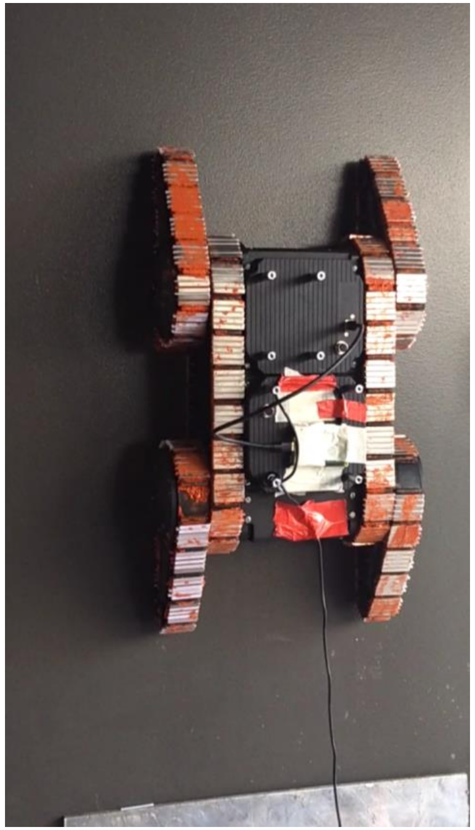



IHA FSW: 400 rpm, 70mm/min & an induction heating power of 15kW

# Project Achievements: Robotic Platform

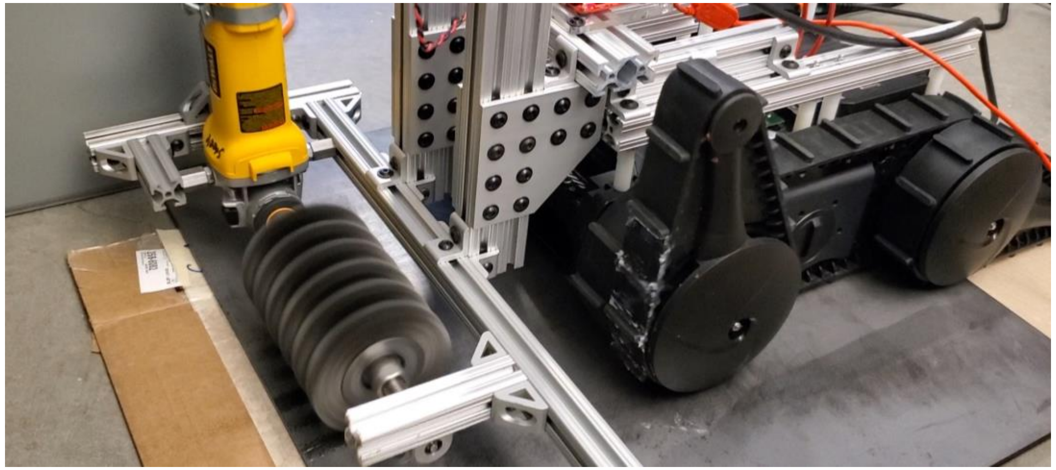
## **Robot Retrofit** (Task 3.1)

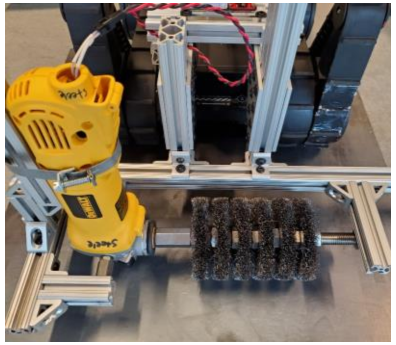
- We modified a tracked mobile robot to include magnets on track surfaces to attach to a vertical metal surface.

## **Cleaning Tool Design** (Task 3.2)

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

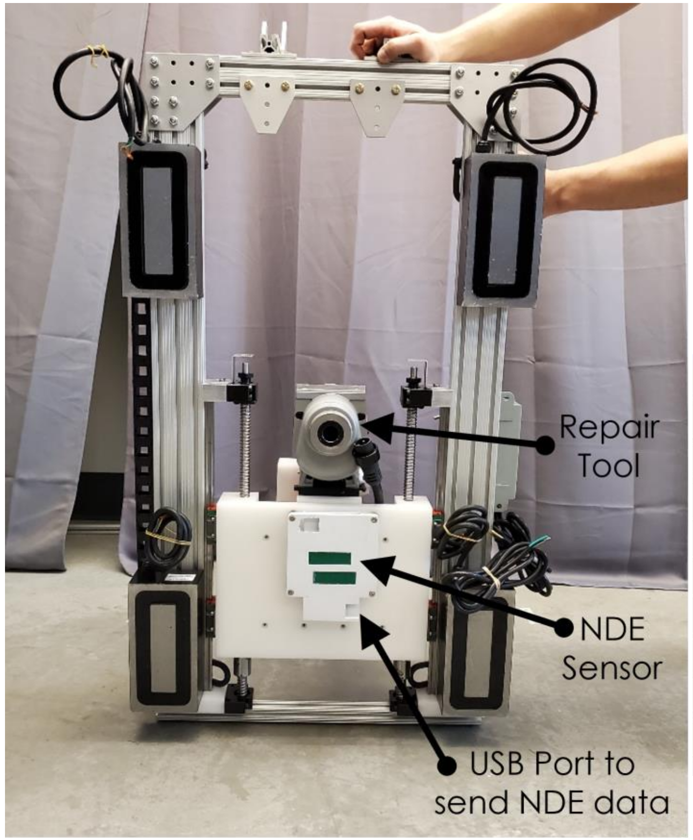


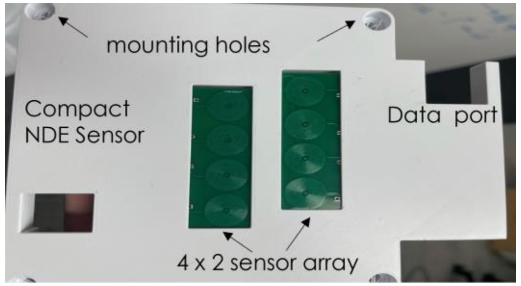


# Project Achievements: Robotic Platform

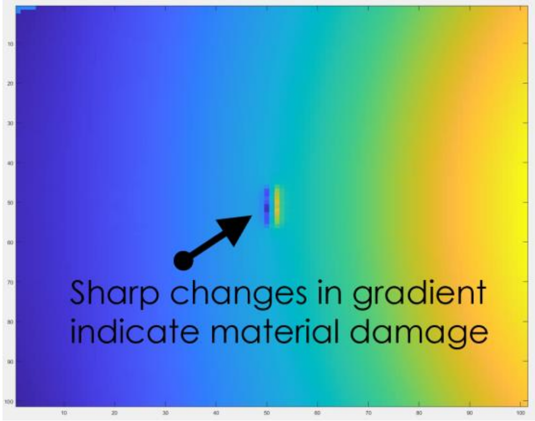
## NDE Sensor Integration (Task 3.3)

- An 8-channel NDE sensor is integrated to the bottom of gantry system and scans along two dimensionalities at a sub-millimeter precision.



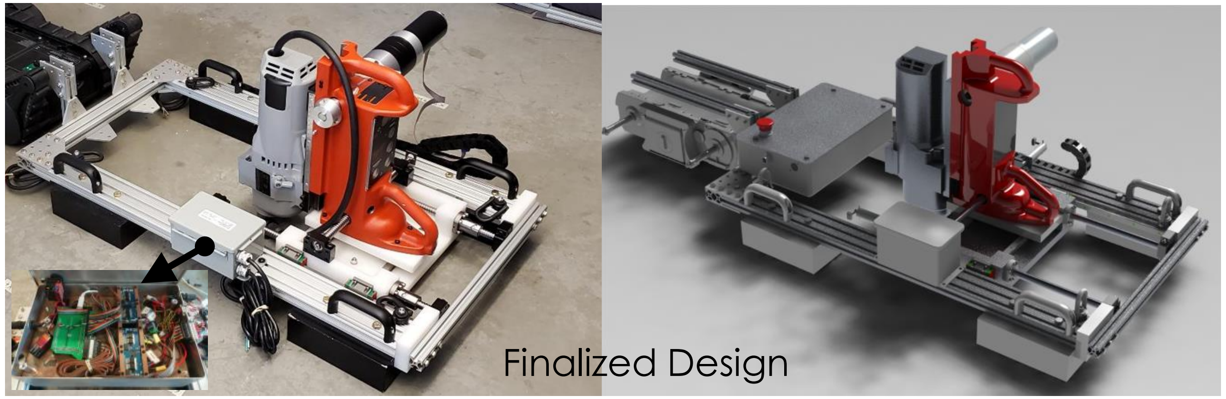

Sensor Bottom View

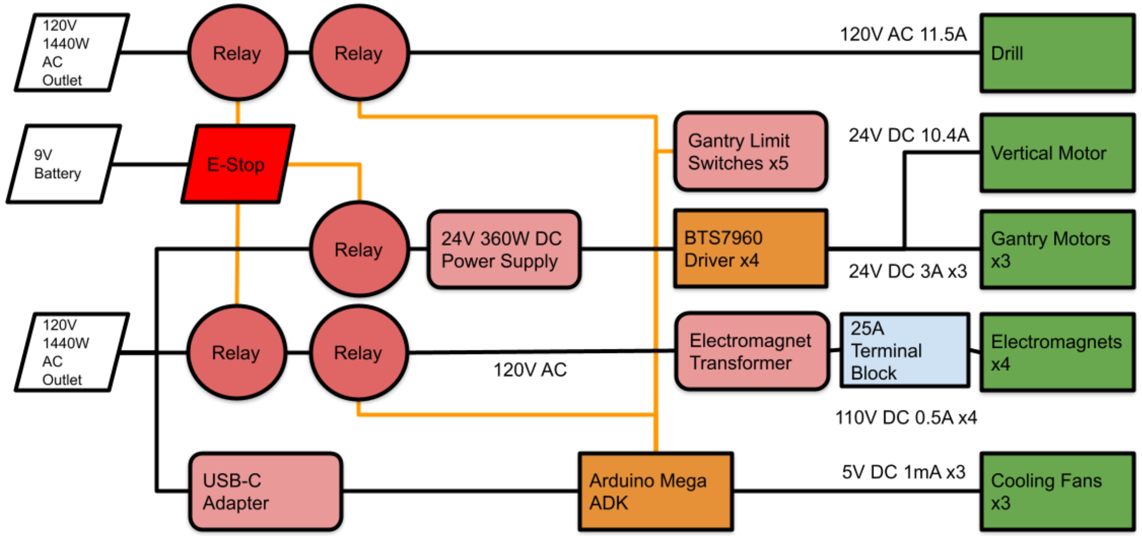



Scan Image Reconstruction

## Repair Tool Integration (Task 3.4)

- A repair tool and a 2-dimensional tool controller are integrated with the gantry system.



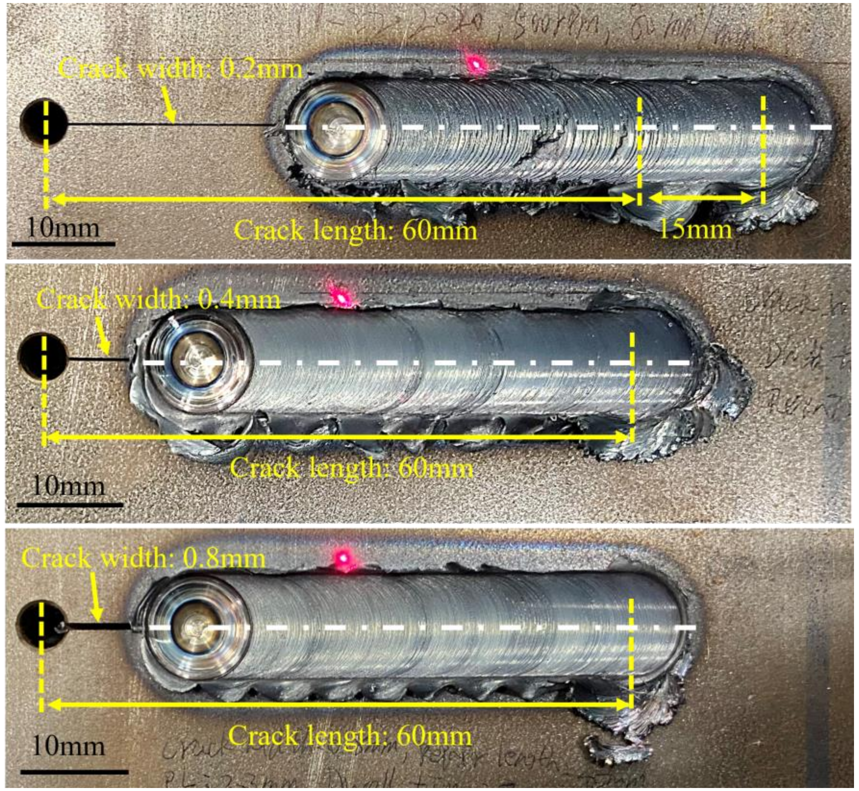




Repair Tool Schematic and Wiring Design

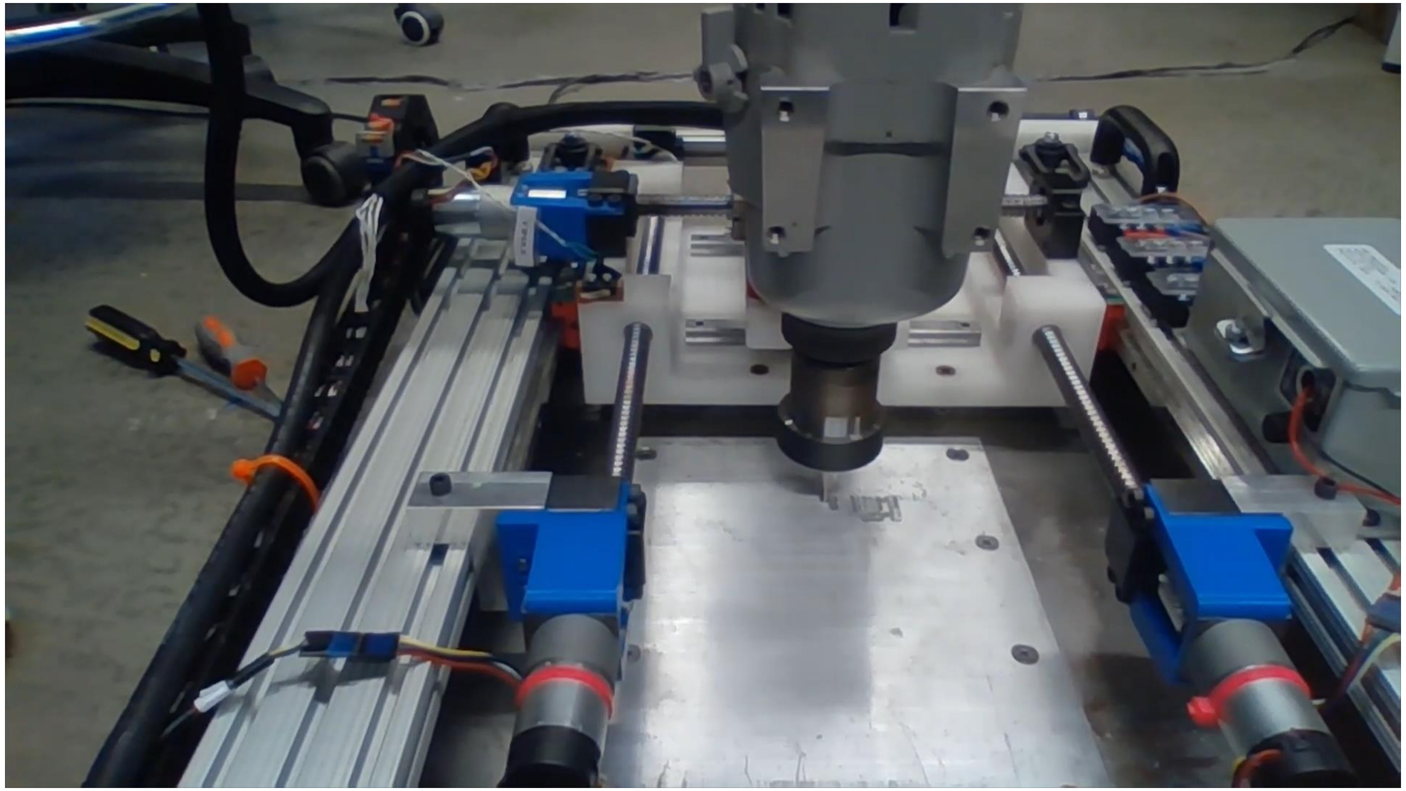
# Project Achievements: Robotic Platform

## Onboard Demonstration and Offboard Repair Evaluation

- Using the tool with a diameter of 10mm, <u>the repair depth is up to around1.6mm, and the width from 0.2mm up to 0.8mm on the A108 steel plate.</u>




Off-board Evaluation

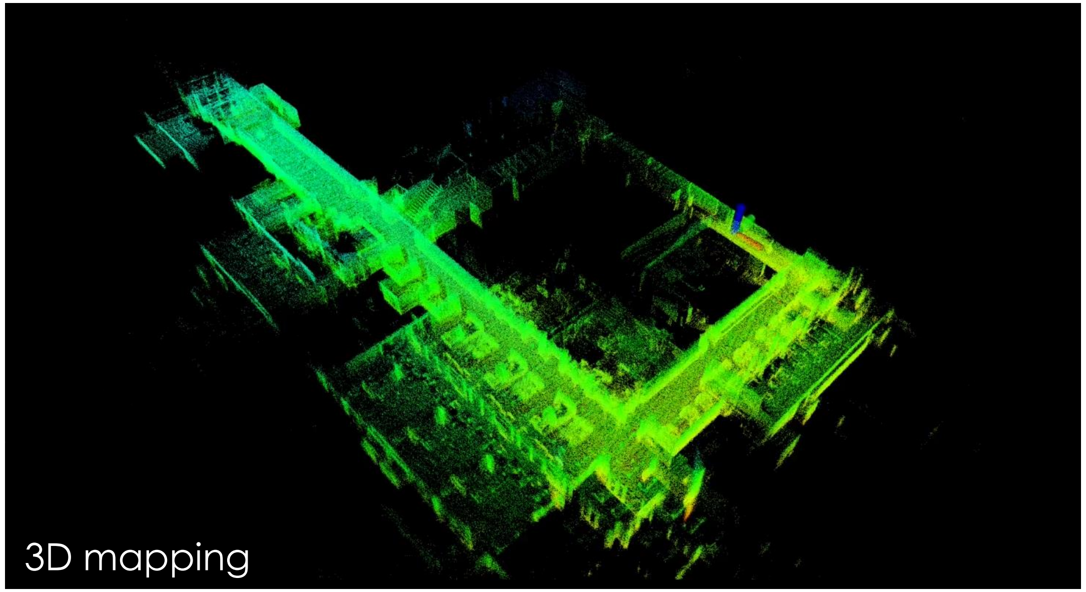


Onboard Demonstration

# Project Achievements: Artificial Intelligence (AI)

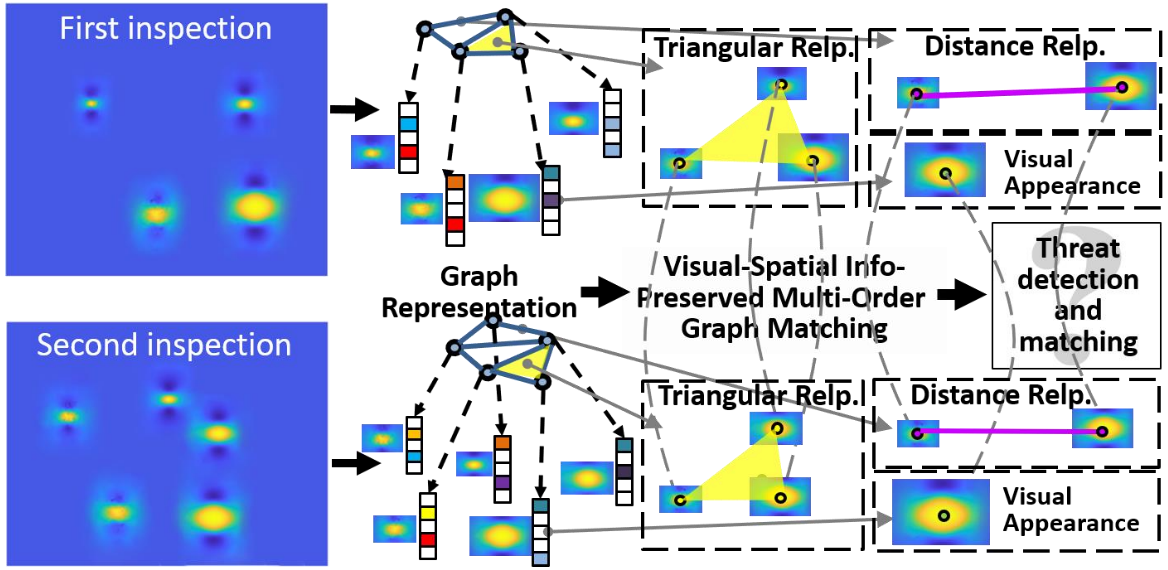
## 3D Mapping & Info Fusion (Task 4.1)

- 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.


3D mapping

## Spatiotemporal Tracking (Task 4.2)

- 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 across inspections.



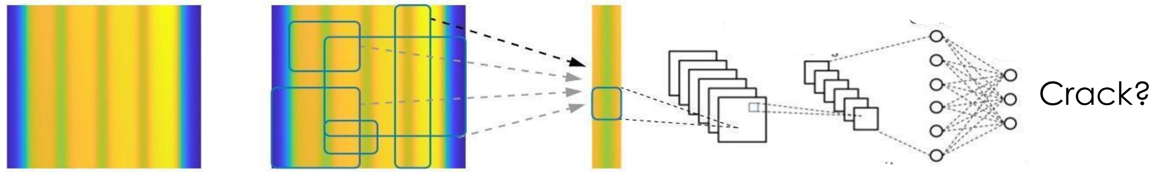

HUMAN-CENTERED ROBOTICS LAB

# Project Achievements: Artificial Intelligence (AI)

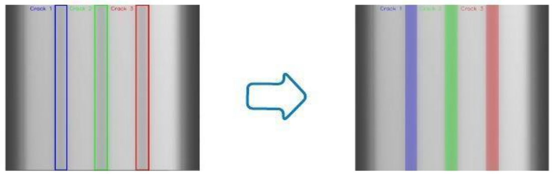
## Machine Learning for Crack Recognition (Task 4.3)

- We developed feature extraction and machine learning methods, e.g., Convolutional Neural Network (CNNs), to recognize simulated cracks.
- The methods obtained > 95% precision and recall.

Shape features: Histogram of Oriented Gradients (HOG)

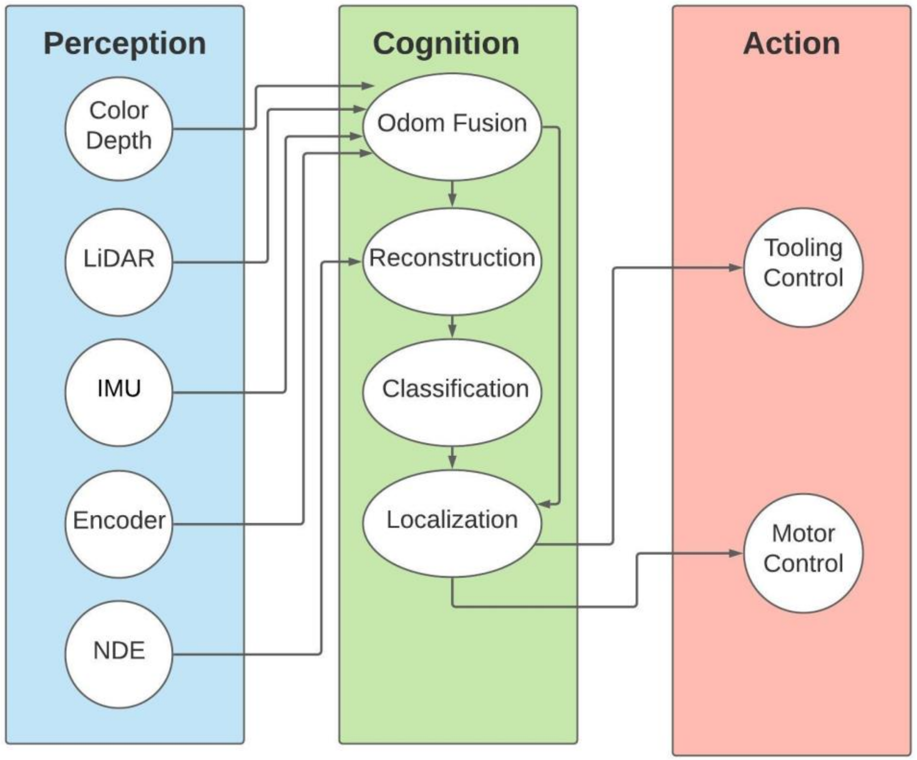



Input Image Extract Region Proposals Neural Network



Overlay Bounding Box Generate Pixel Mask

### Software System Architecture




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

HUMAN-CENTERED ROBOTICS LAB

# Educational Impacts

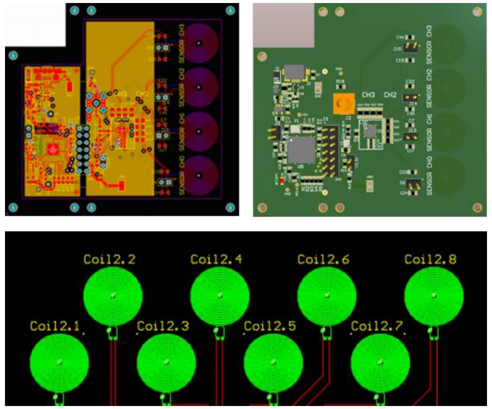
- This project provided opportunities to faculty, graduate students, and undergraduate students for interdisciplinary research in fossil energy fields.
- Research topics from this project were also used as motivating examples in the PIs' courses (e.g., as a topic for final course projects).
- *2020*-Dr. Zhenzhen Yu and Dr. Hao Zhang were promoted to Associate Professor with tenure at the Colorado School of Mines.
- Publication: Related research topics from this project was published at multiple conferences on NDE and robotics, including *ENDE*, *ISEM*, *ICRA* and *IROS*, and by the journal of *Materials Evaluation*.
- *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.

# Insights and Future Work

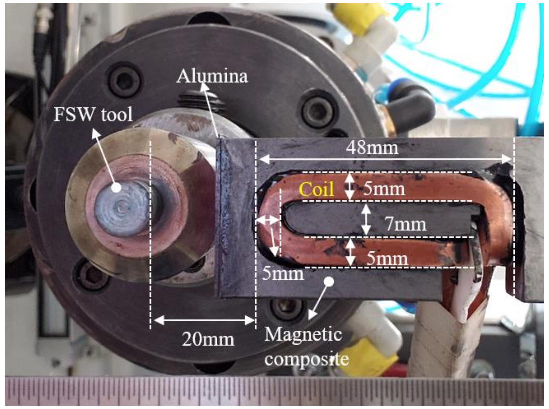
- Designing a portable repair tool and integrating it with the autonomous robot is the biggest challenge. Further development is still required to mature the tool to address the complex geometry of furnace walls.
- Data, data, more data!: Machine learning models, especially deep learning methods, require big data for training. Obtaining real-world large-scale data of boiler anomalies (e.g., cracks) is a big challenge.
- Many future works must be done to continue this basic research in order to move the developed robotic system closer to real-world deployment, and to address many additional challenges, such as:
  - Multi-sensory fusion to integrate NDE data from multiple sources to improve assessment accuracy.
  - Design of robot motions to coordinate the sensor and the repair tool for real-time integrated and iterative assessment and repair.
  - Navigation planning for the robot to intelligently cover all furnace walls in a boiler.
  - Customer discover to understand the project’s impacts, such as time and cost savings, reduced risk for humans, and increased boiler reliability, usability, and efficiency.

# Concluding Remarks

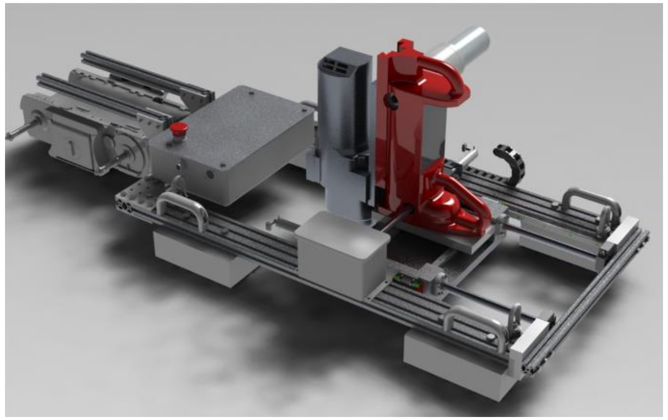
- This project developed an autonomous robot that is equipped with NDE sensors to perform real-time inspection, operate repair devices to achieve live repair, and use artificial intelligence to enable smart data analysis and autonomy, in order to address cracks on boiler furnace walls.



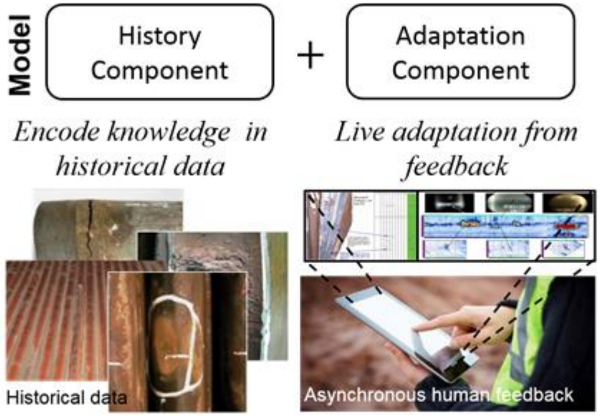

NDE Sensing and Assessment




Repair Device Design and Control



Robot Platform Integration




Artificial Intelligence

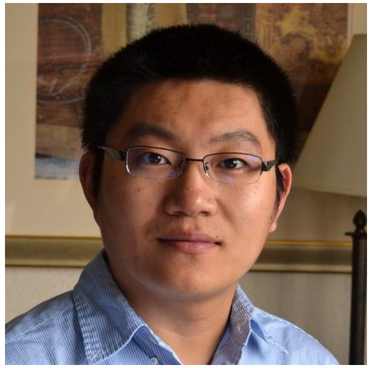
HUMAN-CENTERED ROBOTICS LAB

# Acknowledgment and Disclaimer


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

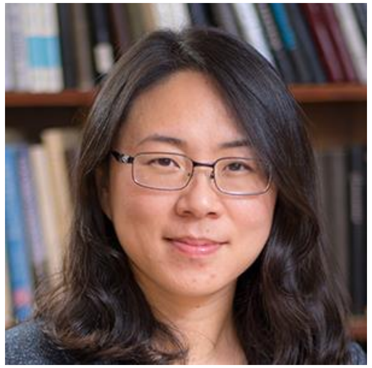
- This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, 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:

Erzhuo Gao

Stewart Grimshaw

Zachary Nahman

Janae Oden

Anthony Olvera

Xiaodong Shi

Lucas Utke


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