# A Robotics Enabled Eddy Current Testing System for Autonomous Inspection of Heat Exchanger Tubes

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**2021 FE R&D Virtual Project Review Meeting: Sensors and Controls**

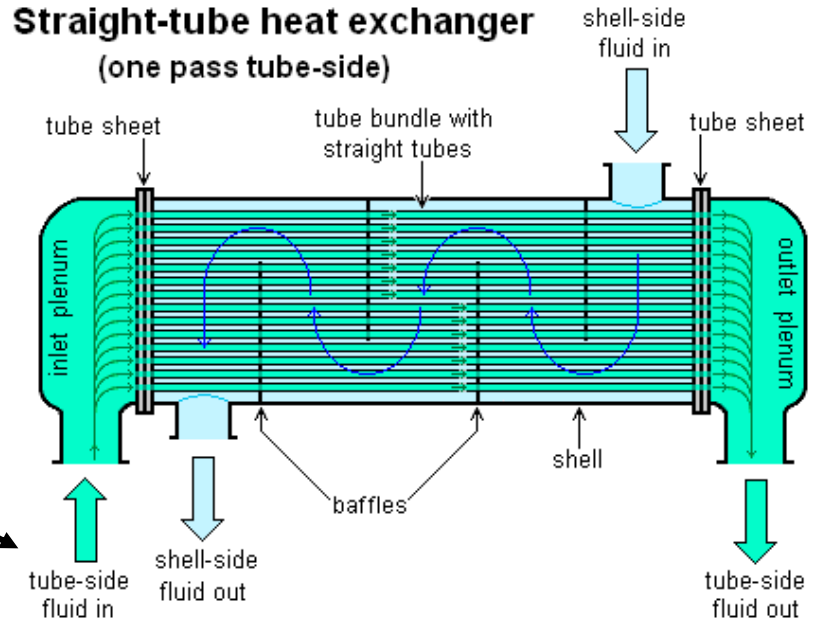
**05/18/2021**

# Heat Exchanger Tubes in Power Plants

Heat exchangers in power plant

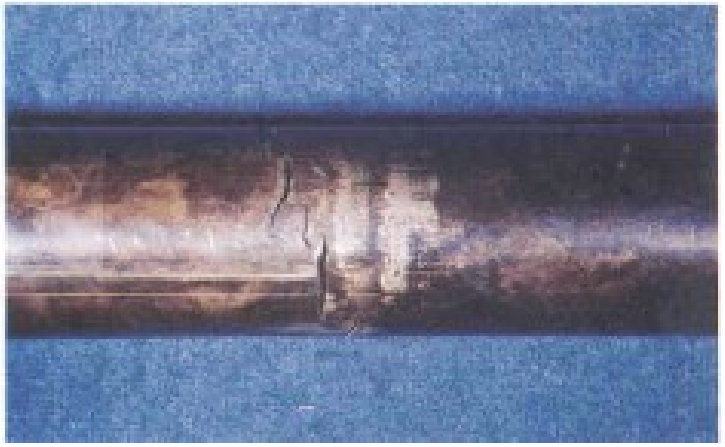

https://fr.dreamstime.com/photo-stock-%C3%A9changeur-de-chaleur-%C3%A0-l-usine-de-raffinerie-image56323288

Shell & tubes heat exchangers



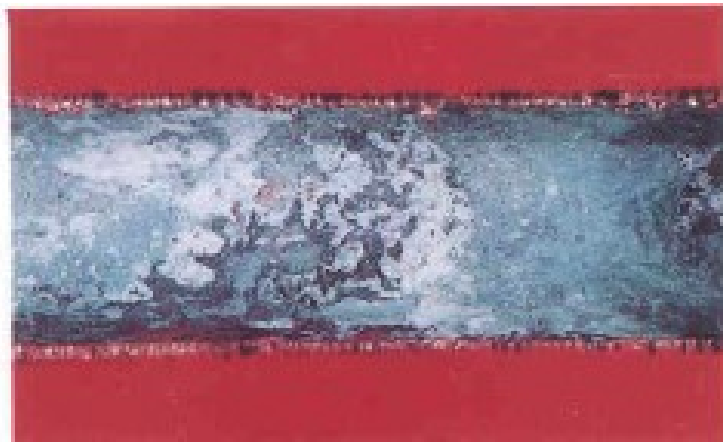

https://en.wikipedia.org/wiki/Shell_and_tube_heat_exchanger

# Failures of Heat Exchanger Tubes

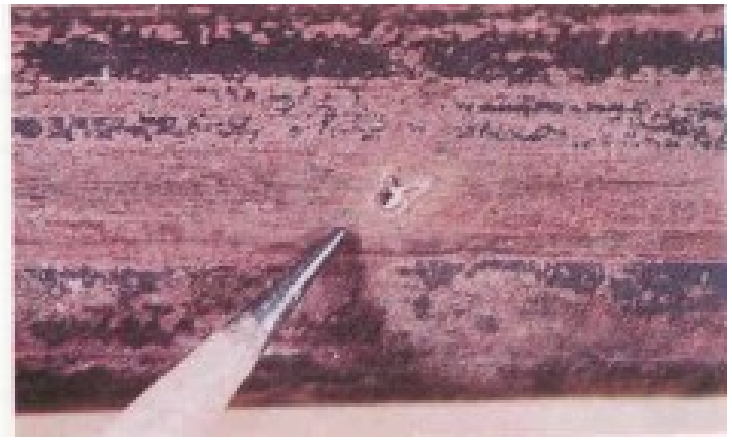


Stress corrosion

Stress cracking

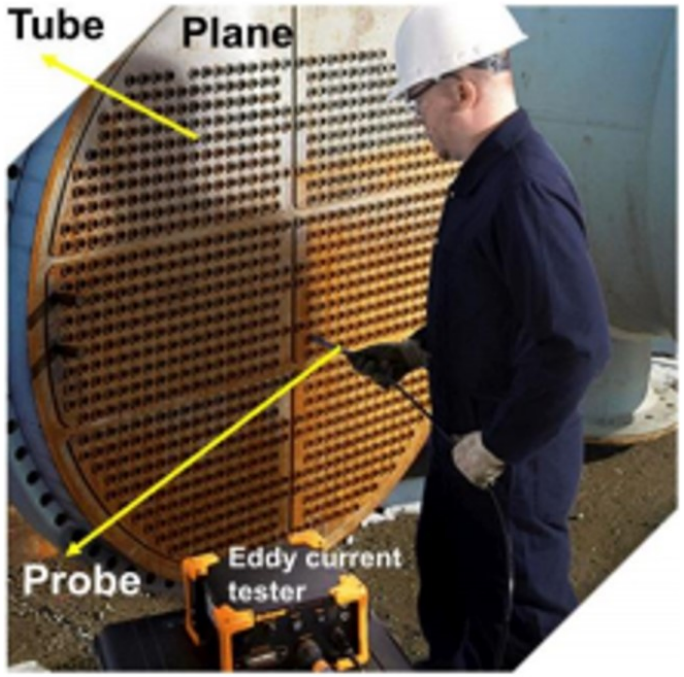


General corrosion inside copper tube because of $CO_2$



Oxygen pitting attack on copper tube

# Current State-of-Art and Problems




The human inspection of heat exchanger tubes

https://mistrasgroup.co.uk/tube-inspection/

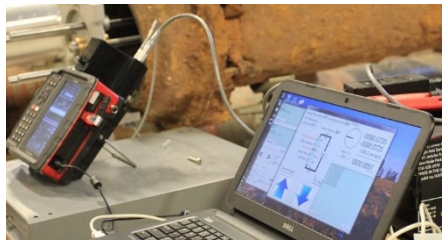
- Labor intensive: routine insertion and extraction of a probe
- Well-trained technicians to operate
- Inconsistent data collection
- Decision making essentially relies on the technician's experience: historic data may not be properly documented and utilized.

A robotic platform that can recognize tube location, perform actuation, and do the testing in an autonomous manner has not been demonstrated for solving the aforementioned problems.

# Challenges of Developing Robotic Platform for Autonomous Inspection

Requirement → The robot that can recognize the object and tube position → Solution → **Machine Vision**

Requirement → Precise control over motion of the ECT probe according to the inlets position of the tubes → Solution → **Accurate Actuation and Agile control Algorithm**

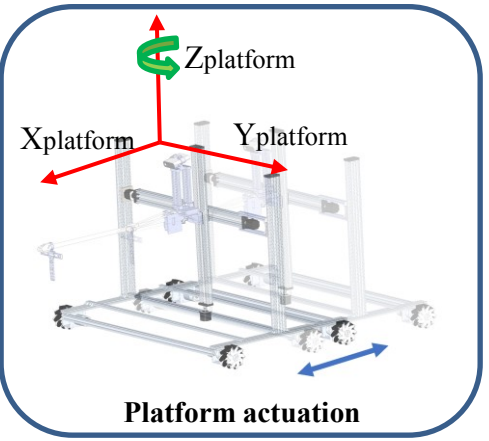


Requirement → Autonomous inspection and analysis capability for decision making → Solution → **Machine Learning Algorithm**

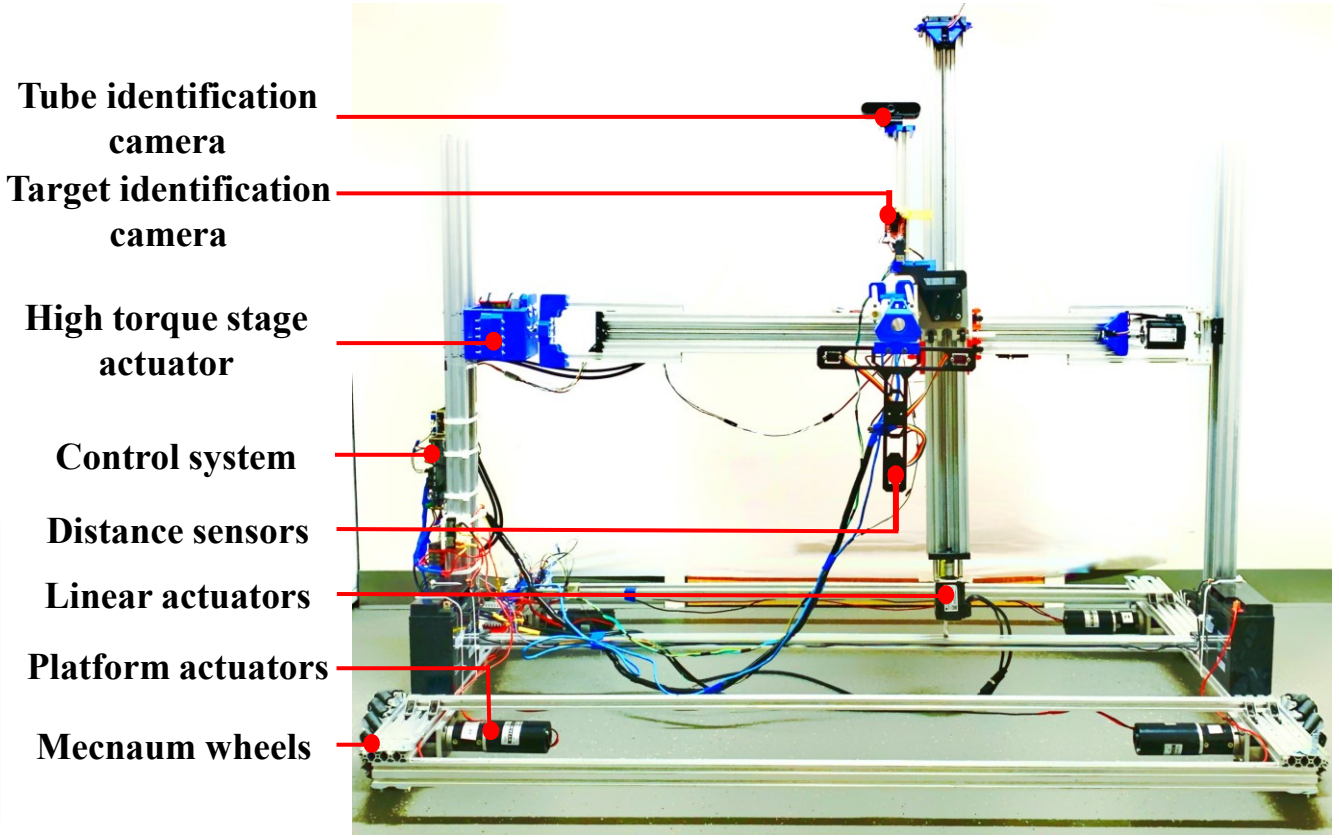
| Yeara | Milestones | Performance Target | Current Status |
|---|---|---|---|
| Q1 2019 | An imaging system that can identify geometry and locations of heat exchange tubes | • Deliver an imaging system that can identify the position map of tubes with an error < 3%.<br>• Deliver a sophisticated image processing algorithm. | ✓ Employ a machine vision system for recognizing object and identifying the location indexes of tubes.<br>✓ Developed algorithm can accurately locate the location indexes of tubes. |
| Q2 2020 | An adaptive control system that precisely controls the position and motion speed of ECT probes | • Deliver a flexible and robust robotic platform to accurately guide movement of the stage and control motions of the ECT probe with a position error of < 3% and a motion speed error of < 2%<br>• Deliver an adaptive control algorithm that can be readily applied in a wide range of fields. | ✓ Completed the structural design of the robotic platform.<br>✓ Parts for the assembly were machined and purchased.<br>✓ Assemble the robotic platform with Mecnaum wheels.<br>✓ Robotic platform is fully functioning to achieve high positioning accuracy and actuation. |
| Q1 2021 | A trained neural network for data analysis and real-time decision making for autonomous inspection. | • Deliver a functional machine learning tool specifically for the eddy current testing.<br>• Obtain a well-trained neural network to predict failure modes of tubes. The prediction error will be < 5%.<br>• Reduce human-induced operating errors and uncertainties. | ✓ Collecting Eddy current data for training machine learning models.<br>✓ Several machine learning algorithms were tested.<br>✓ A data augmentation algorithm was developed and implemented for solving the issue of lack of enough Eddy current spectra. |
| Q3 2021 | Performance of the eddy current tester integrated with the robotic platform meets the requirement. | • Deliver an autonomous testing system meeting required sensitivity and fast response.<br>• Deliver a testing and evaluation protocol for future development and maintenance. | |

# Robotic platform

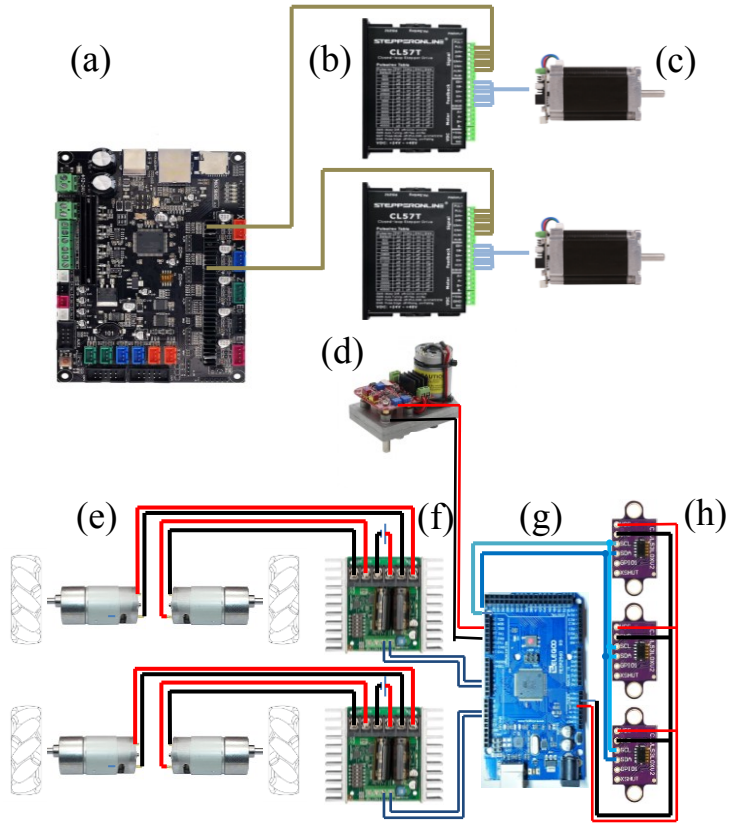
(1)




(2)




(3)

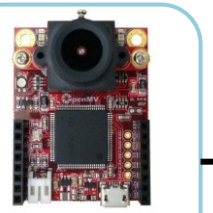



(1) Locomotion of platform and stage. (2) System layout. (3) Control unit

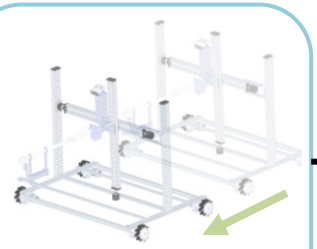
# Summary of main sub-systems and their control flow

Target searching

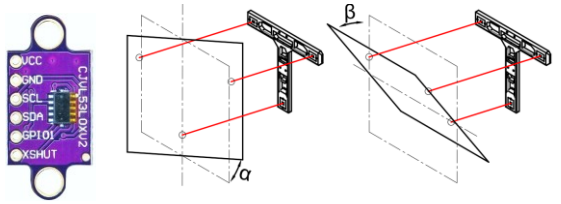
1.Platform positioning



OpenMV smart camera



Platform locomotion




Determine orientation of operational plane through 3 vl53l0x TOF sensors

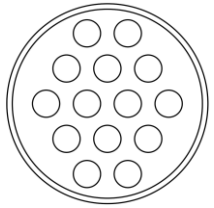
PID Controller (I)-α

PID Controller (II)-β

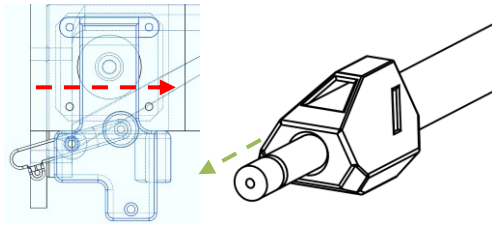

Repositioned platform and stage

2.Tube identification and Tube data collection

HD camera



Detect locations of tube inlets (x,y)



deploy ECT probe at optimum feeding rate

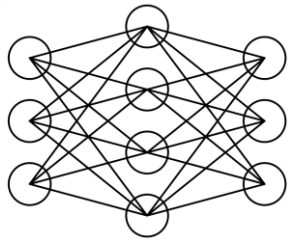
| Tube index | Tube data |
|---|---|
| 1 | |
| 2 | |
| 3 | |

Collecting tube data

3.Tube status classification

| Tube index | Tube data |
|---|---|
| 1 | |
| 2 | |
| 3 | |
| … | |

Collected tube data



Deep learning model

| Tube index | Tube status |
|---|---|
| 1 | cracked |
| 2 | erosion |
| 3 | pit |

Decision making

Yes

other targets detected?

No

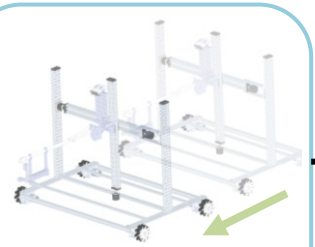
Mission finished

# Subsystem 1 – Target searching and positioning

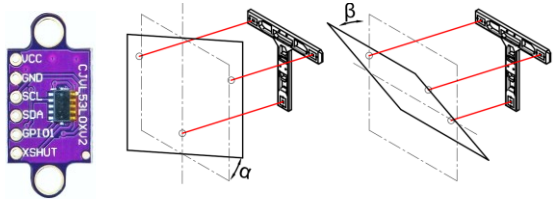
**Target searching**

**1.Platform positioning**

OpenMV smart camera



Platform locomotion




Determine orientation of operational plane through 3 vl53l0x TOF sensors

PID Controller (I)-α

PID Controller (II)-β


Repositioned platform and stage

**2.Tube identification and Tube data collection**



HD camera



Detect locations of tube inlets (x,y)



deploy ECT probe at optimum feeding rate




Collecting tube data

**3.Tube status classification**




Collected tube data



Deep learning model




Decision making

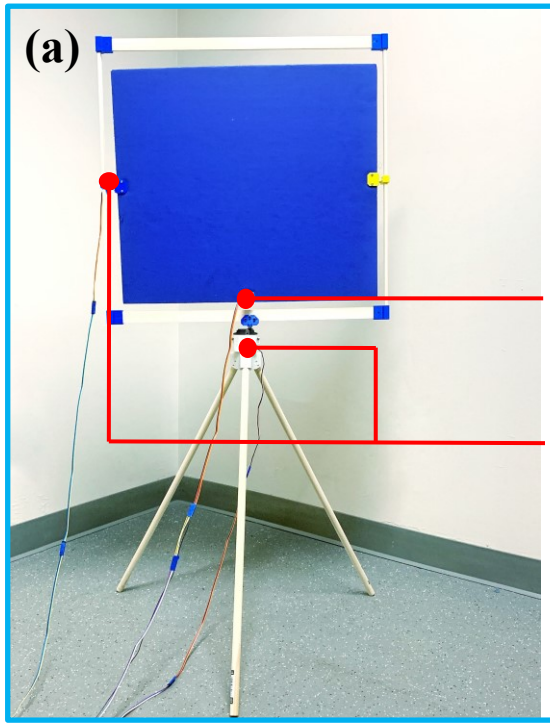
Yes

other targets detected?

No

Mission finished

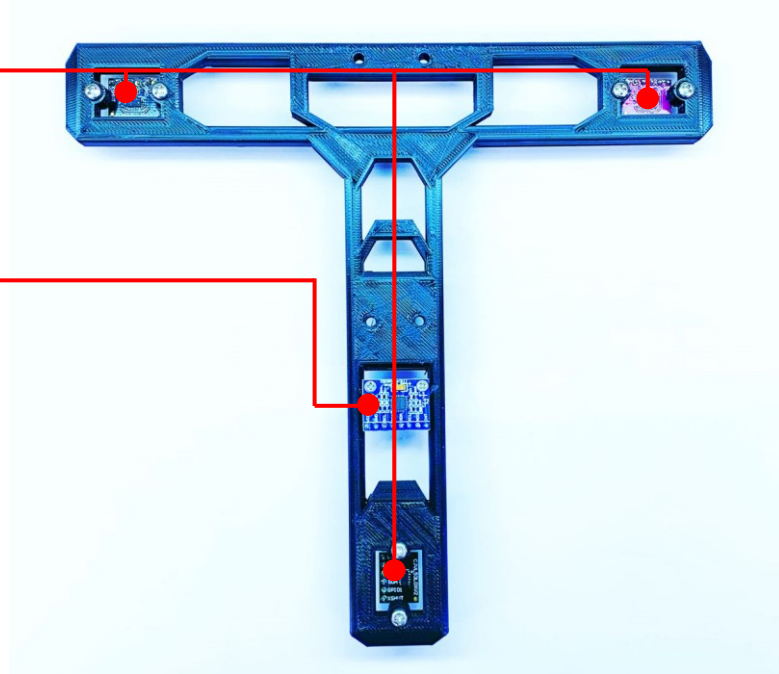
(a)



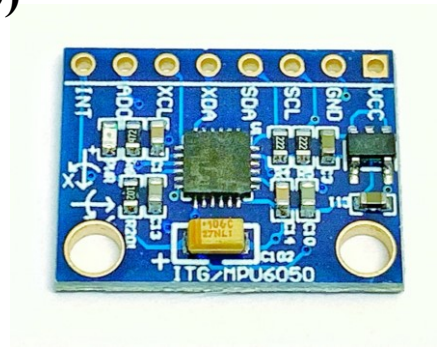
TOF distance sensors

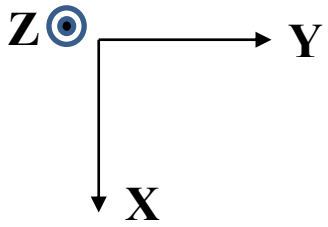
Gyroscope

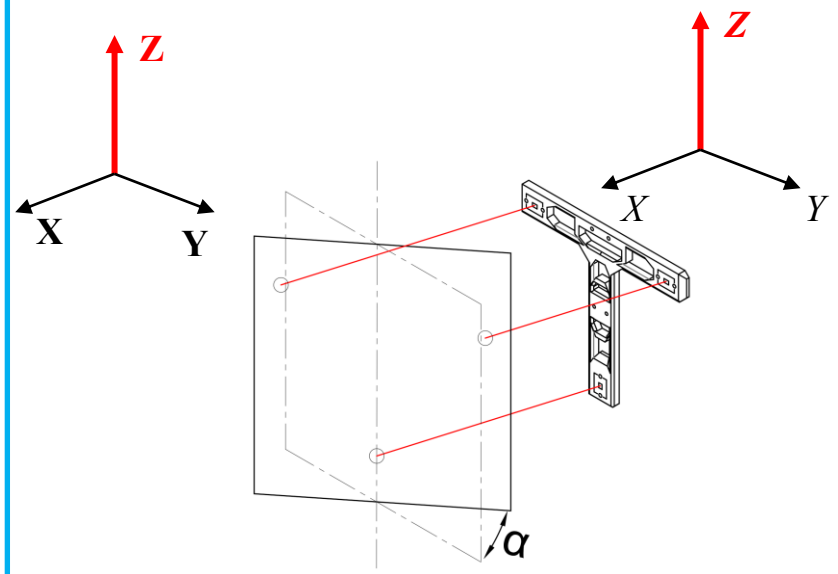
Servo motors

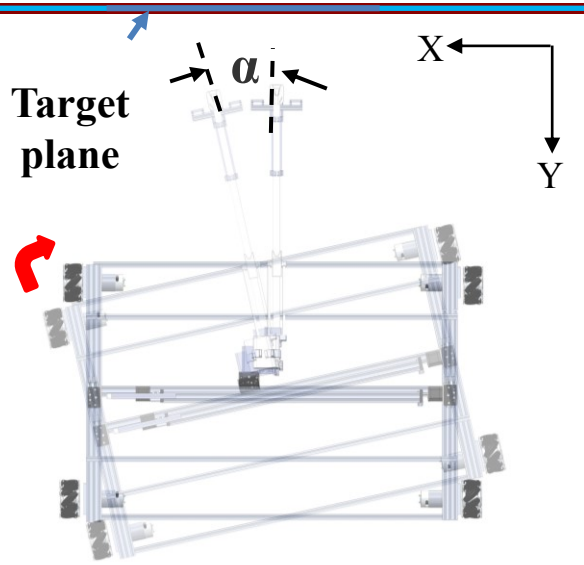


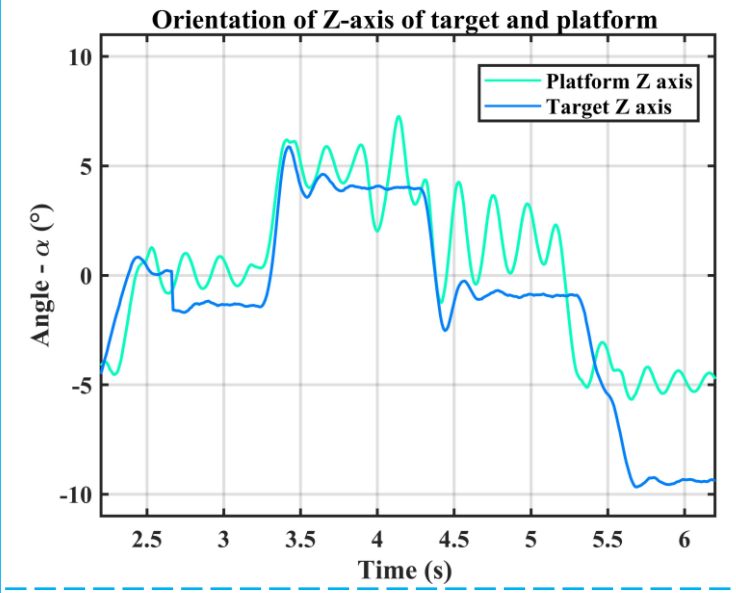
(b)

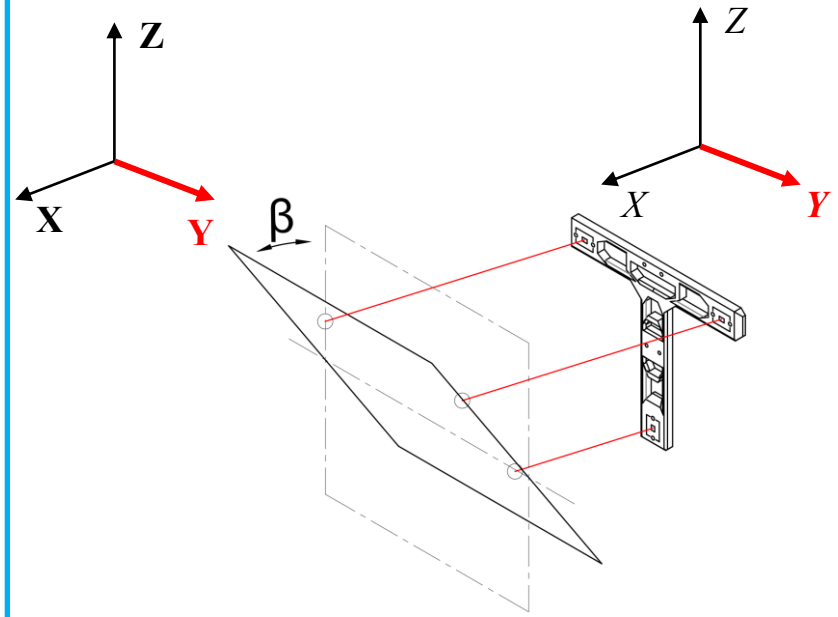


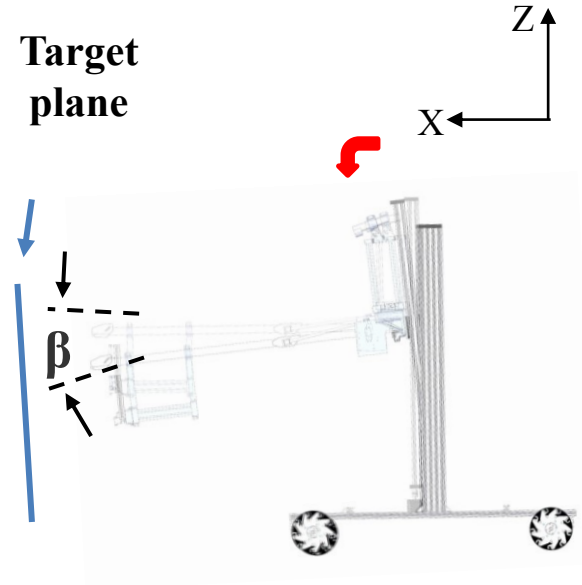



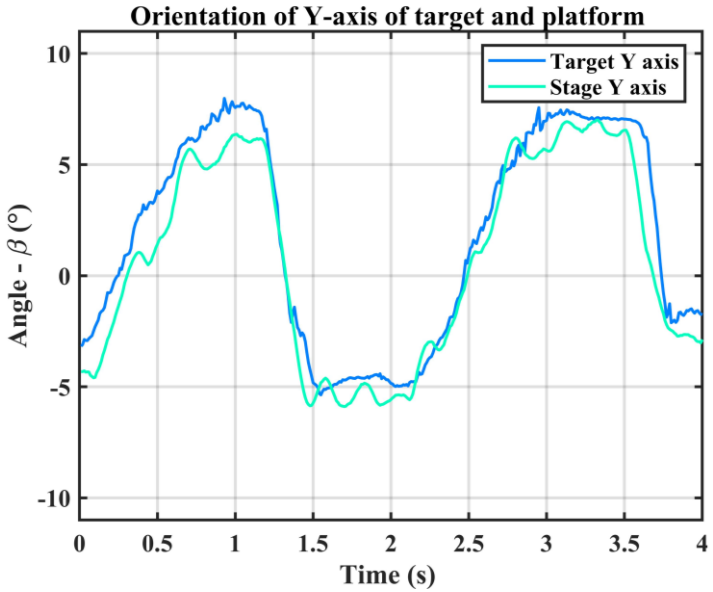

Z
X
Y
Z
X
Y
α


Target plane
α
X
Y

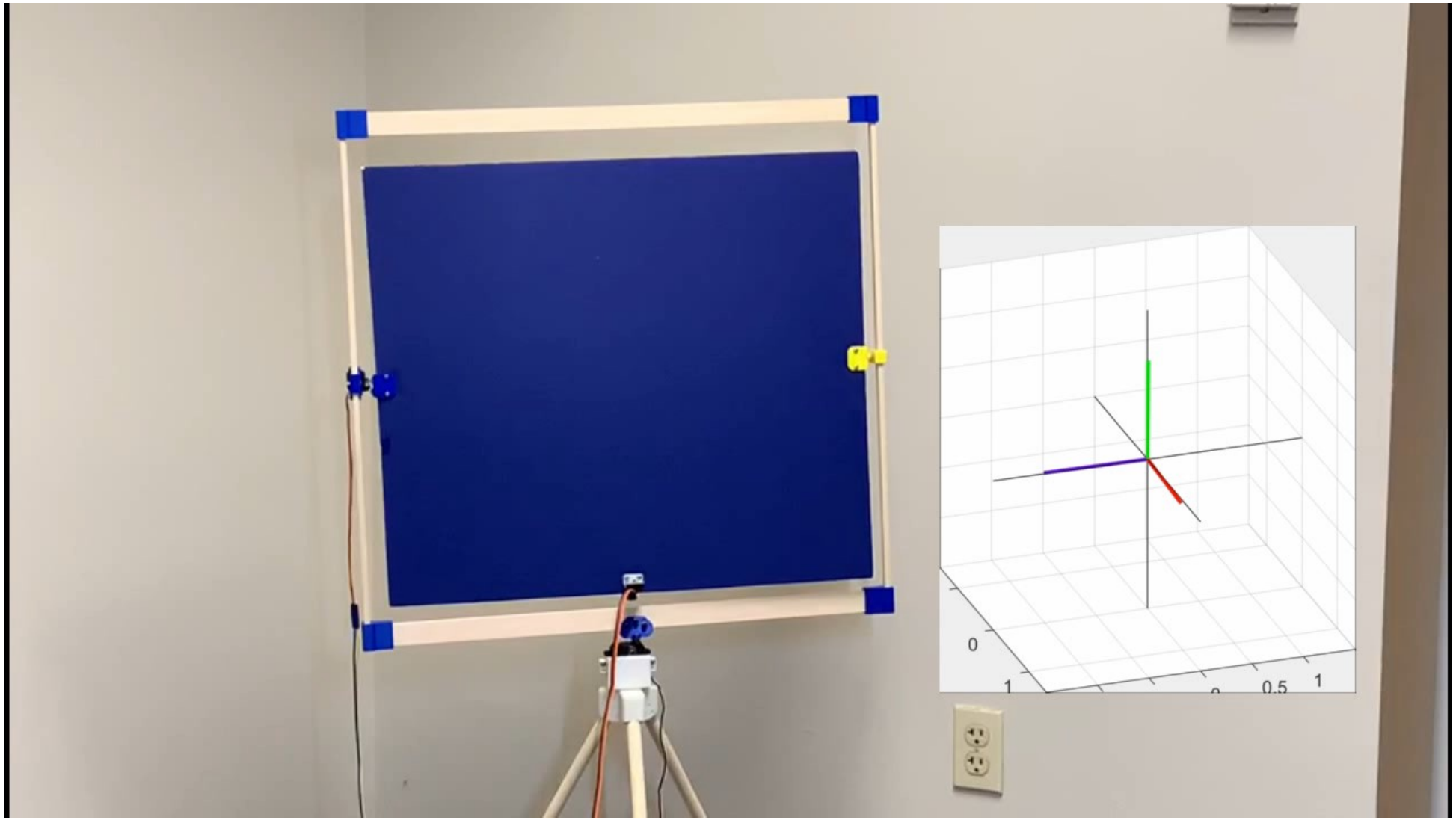

Orientation of Z-axis of target and platform
Platform Z axis
Target Z axis
Angle - α (°)
Time (s)


Z
X
Y
Z
X
Y
β


Target plane
Z
X
β


Orientation of Y-axis of target and platform
Target Y axis
Stage Y axis
Angle - β (°)
Time (s)

# Video: platform reposition demonstration



# Subsystem 2 – Tube identification and location index determination

Target searching

1.Platform positioning



OpenMV smart camera



Platform locomotion




Determine orientation of operational plane through 3 vl53l0x TOF sensors

PID Controller (I)-α

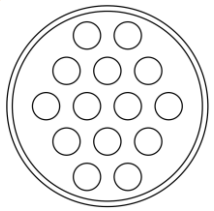
PID Controller (II)-β



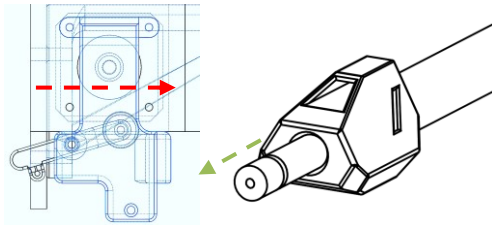

Repositioned platform and stage

**2.Tube identification and Tube data collection**

**HD camera**



**Detect locations of tube inlets (x,y)**



**deploy ECT probe at optimum feeding rate**

| Tube index | Tube data |
|---|---|
| 1 | |
| 2 | |
| 3 | |

**Collecting tube data**

3.Tube status classification

| Tube index | Tube data |
|---|---|
| 1 | |
| 2 | |
| 3 | |
| … | |

Collected tube data



Deep learning model

| Tube index | Tube status |
|---|---|
| 1 | cracked |
| 2 | erosion |
| 3 | pit |

Decision making

Yes

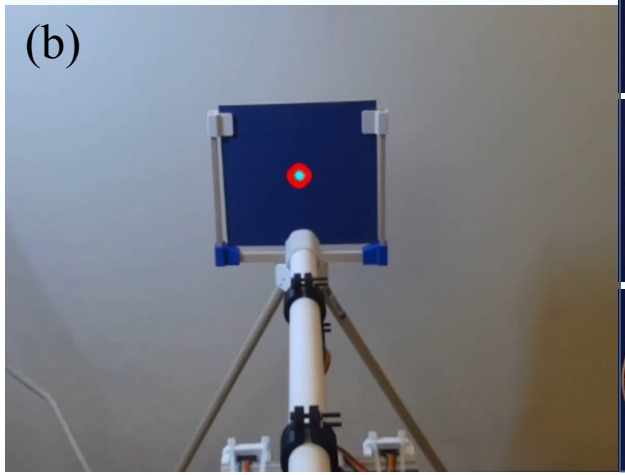
other targets detected?

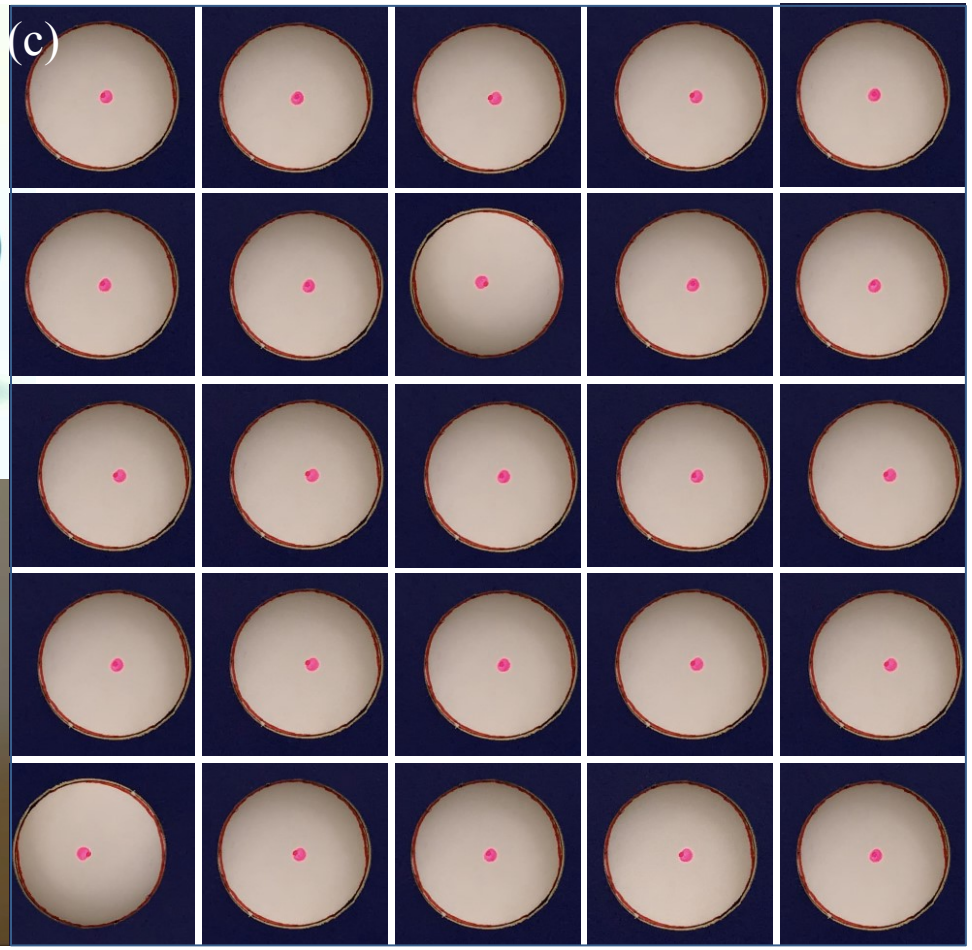
No

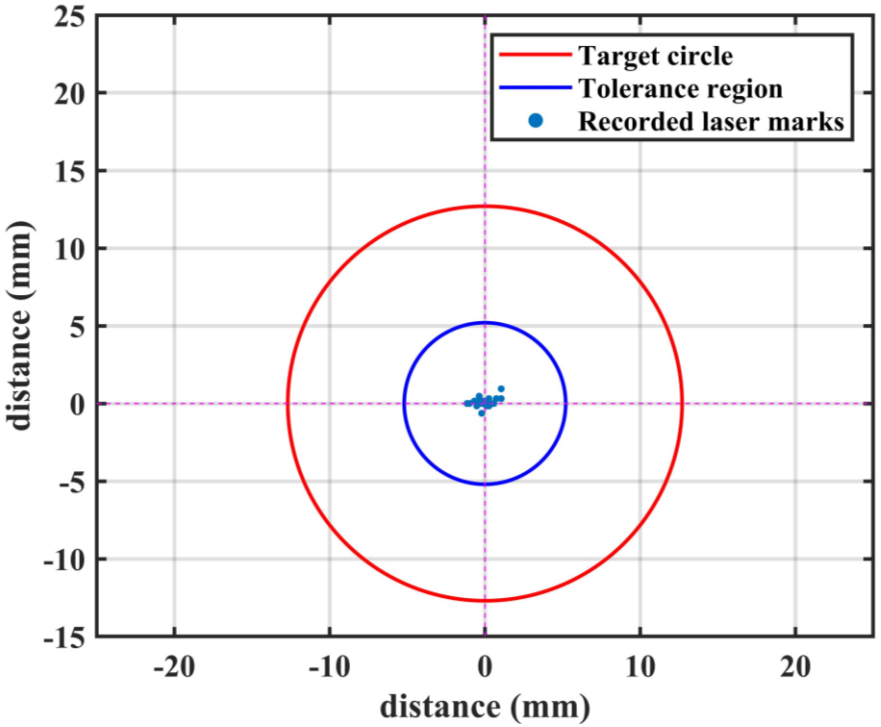
Mission finished

# Video: Machine Vision

# Accuracy of machine vision


Results and evaluation of machine vision, (a) camera used for tube inlet determination, (b) machine vision, (c) collected detection accuracy data, (d) detection results are all in the tolerance region

# Subsystem 3 – Deep learning for tube status classification

Target searching

1.Platform positioning



OpenMV smart camera



Platform locomotion



Determine orientation of operational plane through 3 vl53l0x TOF sensors

PID Controller (I)-α

PID Controller (II)-β



Repositioned platform and stage

2.Tube identification and Tube data collection



HD camera



Detect locations of tube inlets (x,y)



deploy ECT probe at optimum feeding rate

| Tube index | Tube data |
|---|---|
| 1 | |
| 2 | |
| 3 | |

Collecting tube data

3.Tube status classification

Yes

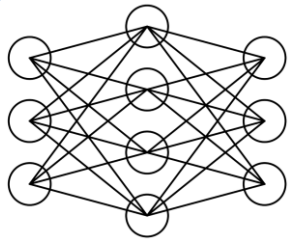
other targets detected?

No

Mission finished

| Tube index | Tube data |
|---|---|
| 1 | |
| 2 | |
| 3 | |
| … | |

Collected tube data



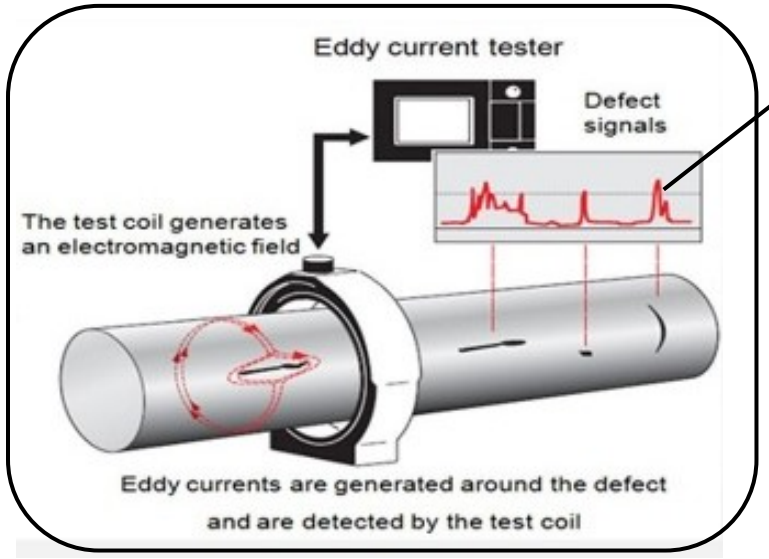
Deep learning model

| Tube index | Tube status |
|---|---|
| 1 | cracked |
| 2 | erosion |
| 3 | pit |

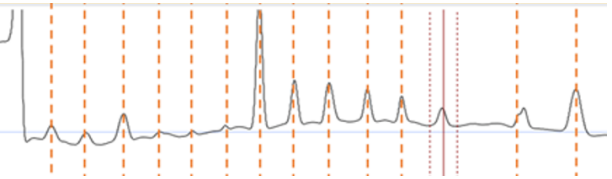
Decision making

**Ongoing**

# Deep Learning for Spectra Data Classification

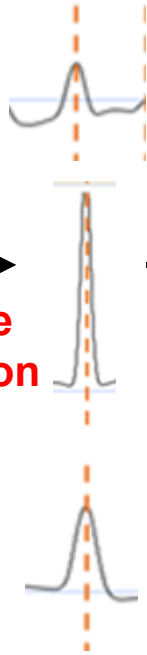



**Eddy current spectrum**

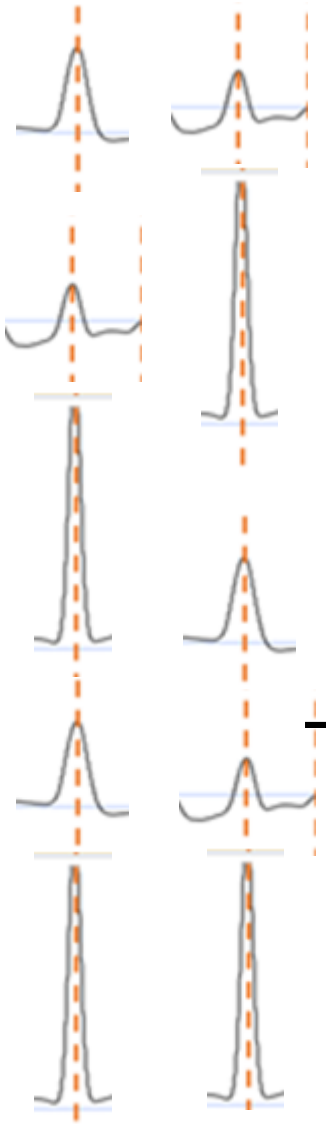


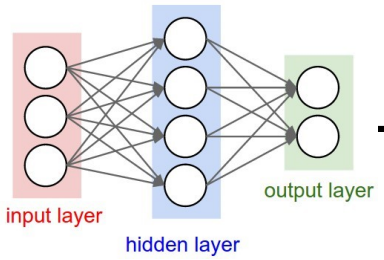
**Collected Spectrum**

**Feature Extraction**



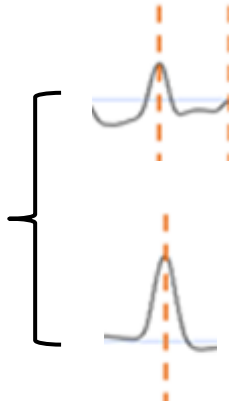
**Data Augmentation**





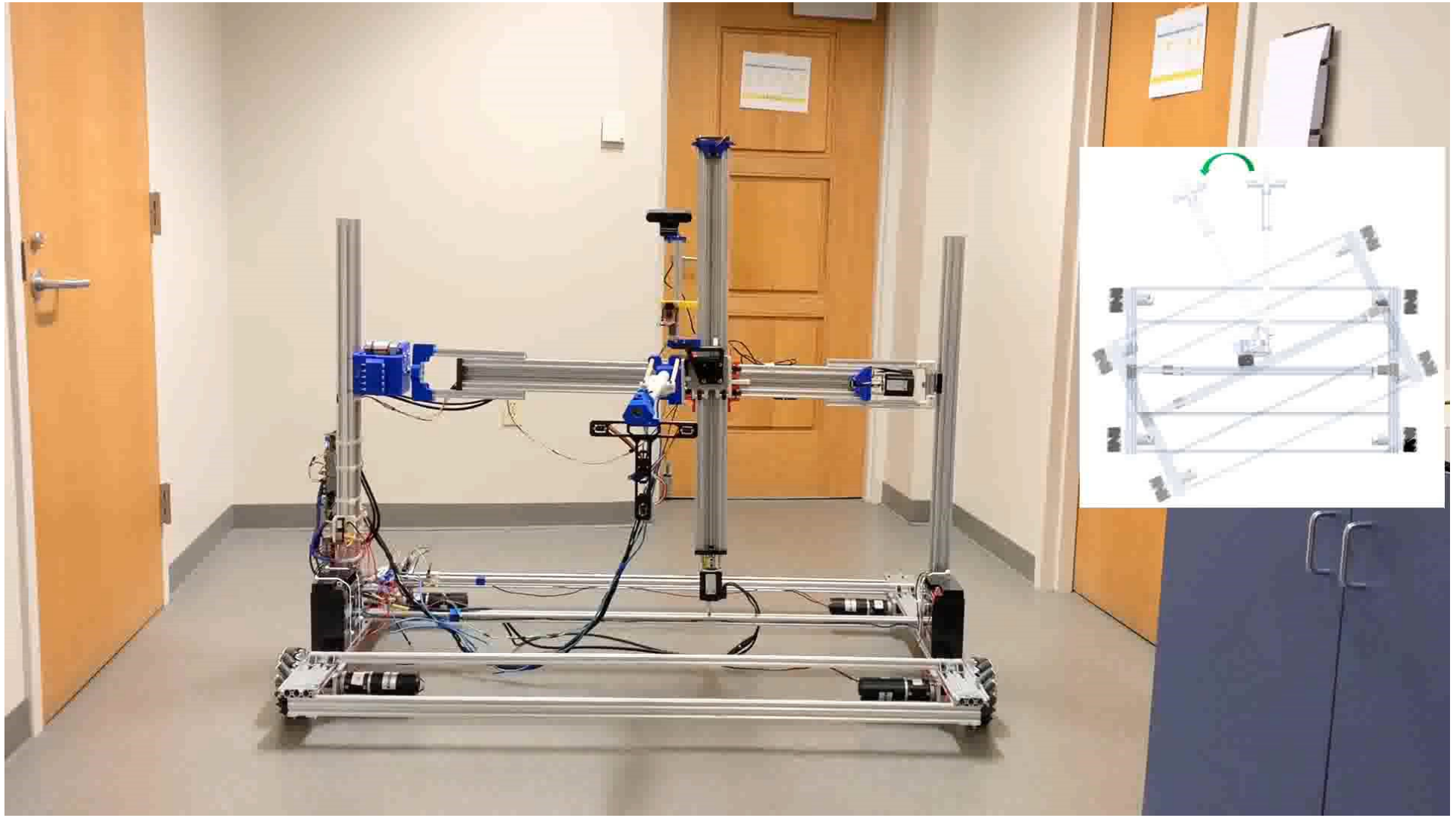

**CNN**

**Big hole**



**Corrosion**

# System Demonstration



# Other Outcomes

Journal Publications Partially Funded by the Grant:

1. Y. Xie, C. Zhang, H. Deng, B. Zheng, K. Shutt, J. Su, and **J. Lin***. Accelerate Synthesis of Metal-Organic Frameworks by a Robot and Optimization Algorithms. ***ACS Applied Materials & Interfaces***, under revision (2021).
2. C. Zhang†, D. Li†, Y. Xie, P. Hua, D. Tung, M. Xin, J. Lin*. Machine learning assisted rediscovery of methane storage and separation in porous carbon from material literature. ***Fuel***, 290, 15 (2021)
3. H. Wang, Y. Xie, D. Li, M. Xin, and **J. Lin***. Rapid Identification of X-ray Diffraction Patterns Based on Very Limited Data by Interpretable Convolutional Neural Networks. ***Journal of Chemical Information and Modeling***, 60, 4, 2004-2011 (2020).
4. Y. Xie, C. Zhang, X. Hu, C. Zhang, S. P. Kelley, J. L. Atwood*, and **J. Lin***. Machine Learning Assisted Synthesis of Metal-organic Nanocapsules. ***Journal of the American Chemical Society***, 142 (3), 1475-1481 (2020).
5. Y. Dong, D. Li, C. Zhang, C. Wu, M. Xin, J. Cheng, and **J. Lin***. Inverse design of two-dimensional graphene/h-BN hybrids by a regressional and conditional GAN. ***Carbon***, 169, 9-16 (2020).

Education and Training

- So far two Ph.D. students, one M.S. student, and four undergraduate students have performed research related to this project.
- Knowledge obtained from the project is integrated to course of “Manufacturing” taught by the PI.

Collaboration with Industrial Partners

- Establish relationship with Eddify which is an eddy current tester manufacturing company. They showed interest in collaboration on autonomous detection enabled by deep learning algorithms.
- Survey the need from local power plants.
- Participate in the field maintenance of the exchange heat tubes.

# Conclusion

- **Benefits**
  - Autonomous robots for testing the exchange heat tube can fill the market gap that calls for increasing automation for power plant maintenance.
  - Autonomous decision making enabled by deep learning the eddy current testing data will provide a new opportunity for the eddy current testing market.
- **Technology-to-Market Path**
  - The developed control algorithm and software can be integrated into existing eddy current tester manufacturers.
  - The developed robotic platform can achieve autonomous testing and automate the power plant maintenance, laying foundation for future research in developing field robots.
  - Working closely with industry collaborators for understanding the market need and technology transfer will be needed.

# Acknowledgement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*Thanks for your attention!*

**Questions?**

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