# A Lizard-inspired Tube Inspector (LTI) Robot

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# Project Description and Objectives

## Problem statement

Thinning

Deposit corrosion

Pitting corrosion

Stress corrosion cracking

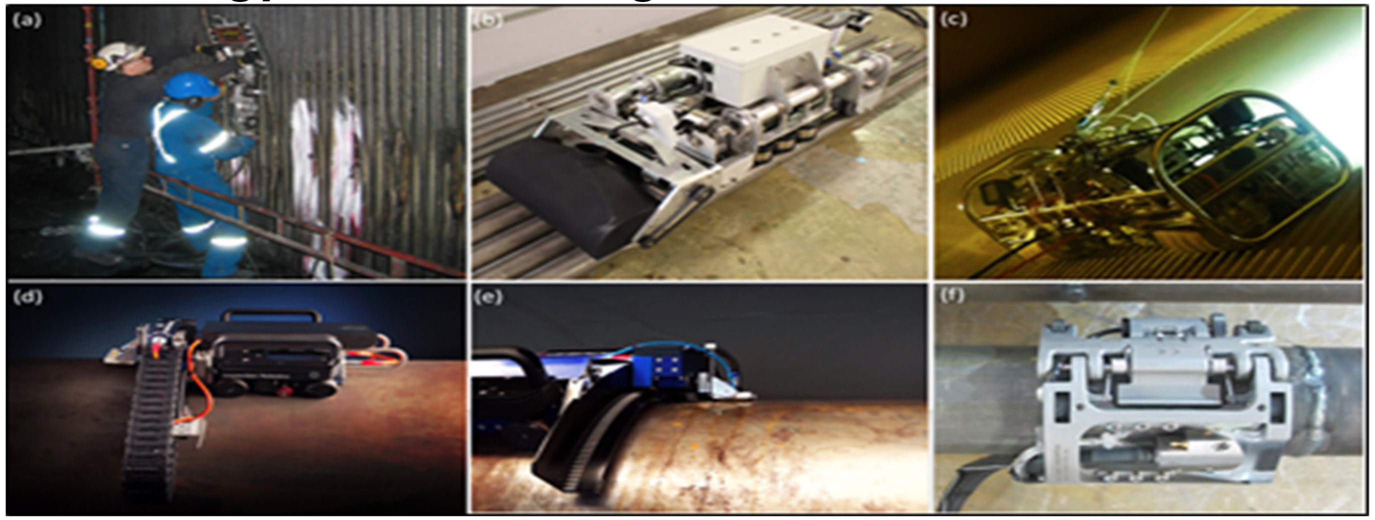
- Tubes and pipelines are the main component of several units in power plants and oil, gas and water transmission.
- Aging power plants and pipelines is a major concern in the US.
- regular inspection is time consuming and costly (e.g. limited accessibility in power plants' units requires overhaul of units for routine inspection )

**A Promising Solution is Robotic Inspection**

# Project Description and Objectives

## Current Robotic Systems and Limitations

**Technology benchmarking**




Tube inspection robots. (a) Vertiscan system, (b) ICM climbing robot, (c) boiler wall cleaning and inspection robot, (d) inspection robotics system, (e) FAST UT system, and (f) PALM scanner.

**Limitations:**

- Cannot be used on complex geometries
- Require smooth surfaces
- Mostly require ferromagnetic materials
- Scanning has to be performed point-by-point
- Testing requires couplant

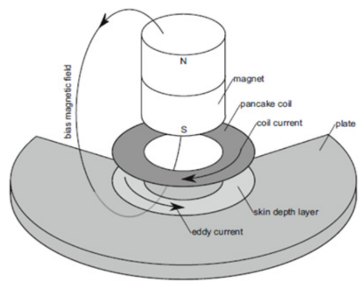
# Project Description and Objectives

## What do we propose?

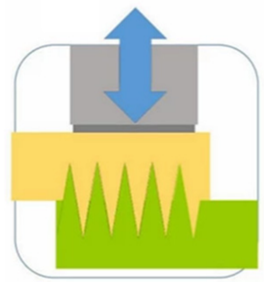
- **Objective 1:** to integrate automation with ***couplant-free*** ultrasound transmission technology and develop an ***advanced Lamb wave based imaging algorithm*** to detect and evaluate crack and corrosion defects in tubes/pipes using a network of couplant-free ultrasound sensors placed at the location of the robot's grippers.

- **Objective 2:** to develop a robot with ***friction-based mobility capabilities*** to move on tubes with complex geometries, obstacles, and rough surfaces such as a U-bend corroded tubular structures.

**Objective 1**
**Couplant-free ultrasound generation**

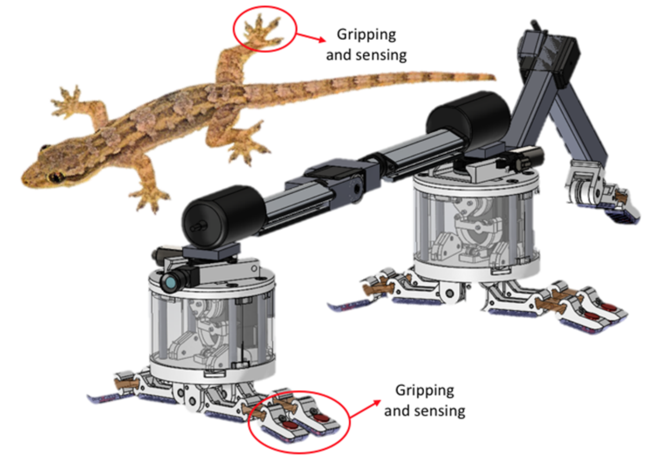



EMAT

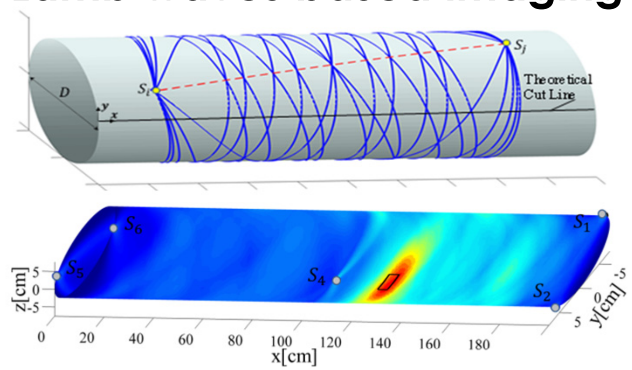


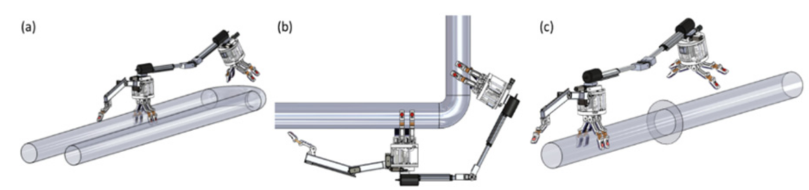
Friction-based ultrasound

**Objective 2**
**Friction-based mobility**

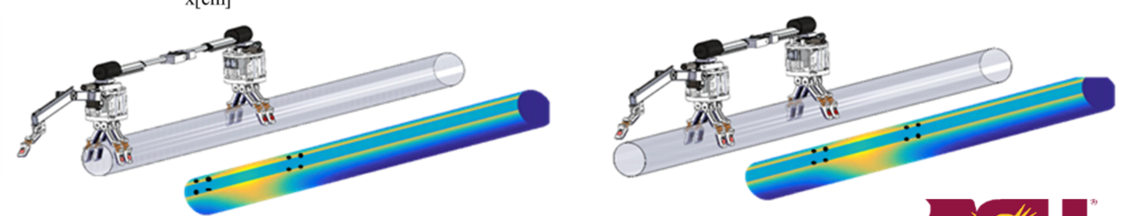



**Lamb waves based imaging**



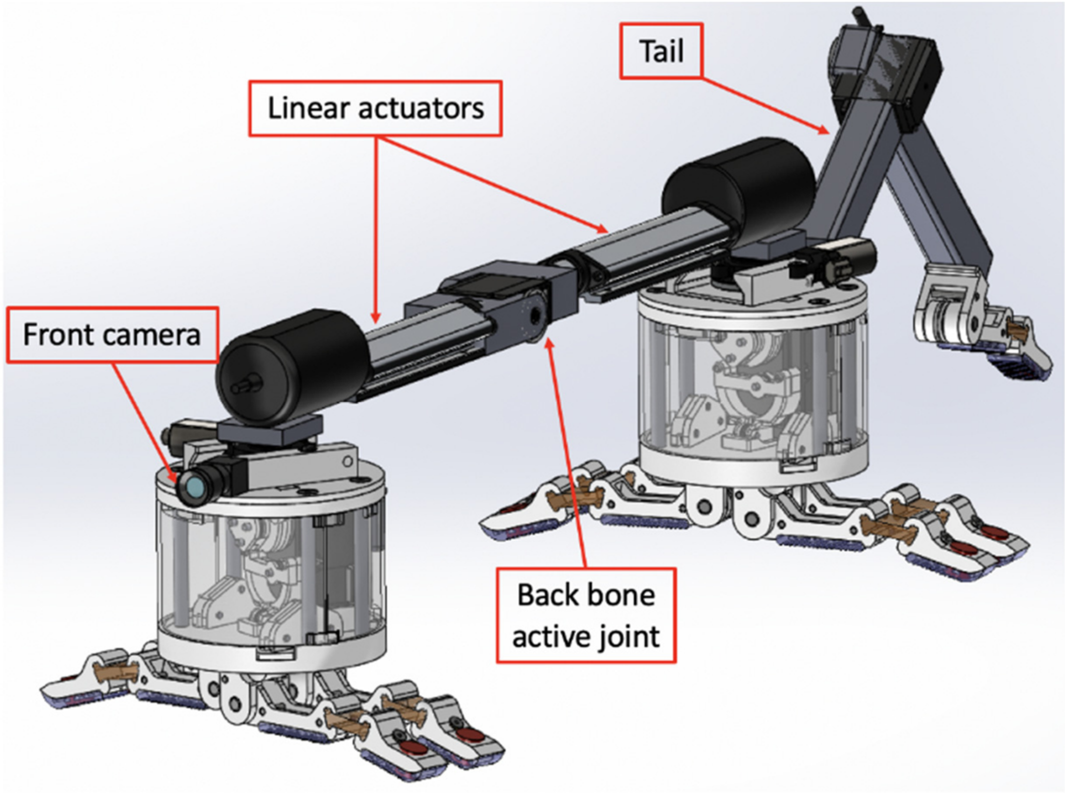

**Final Goal**



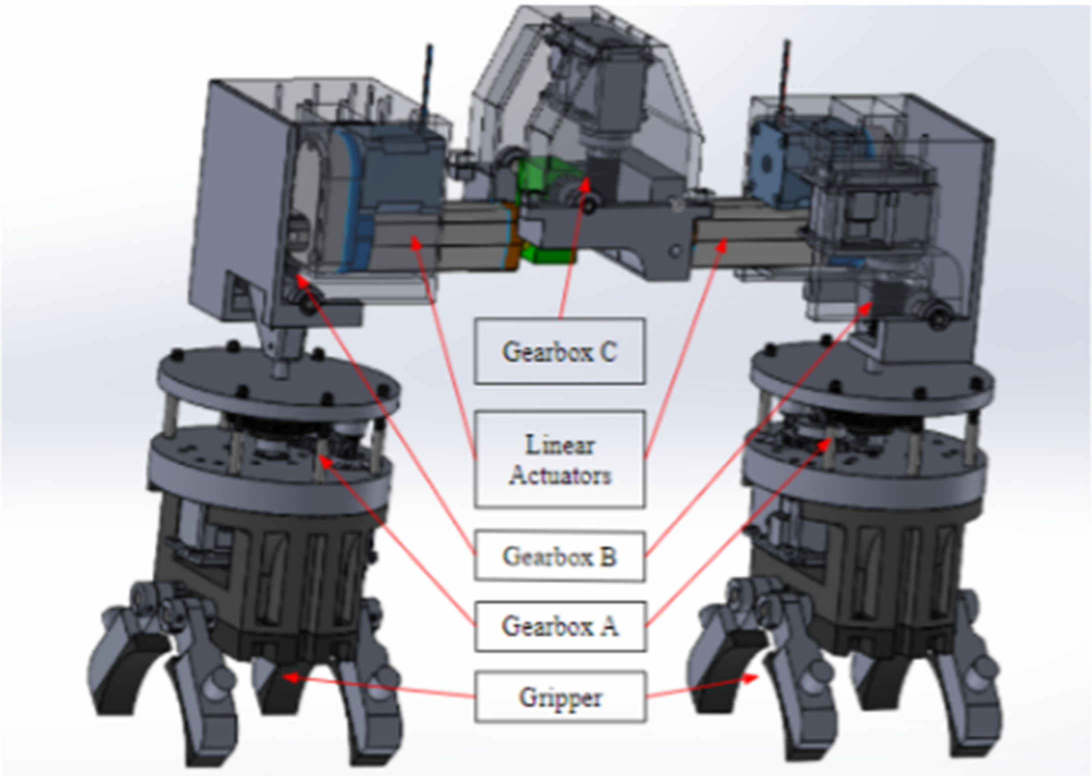
# Lizard-inspired Tube Inspector (LTI) Robot

## Original concept vs. Current design

Original concept



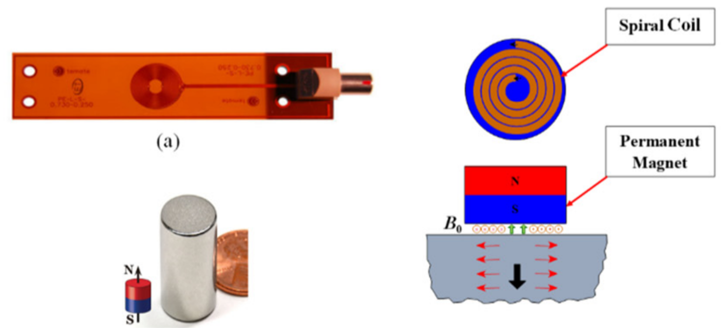

Current design



# Couplant-free ultrasound generation

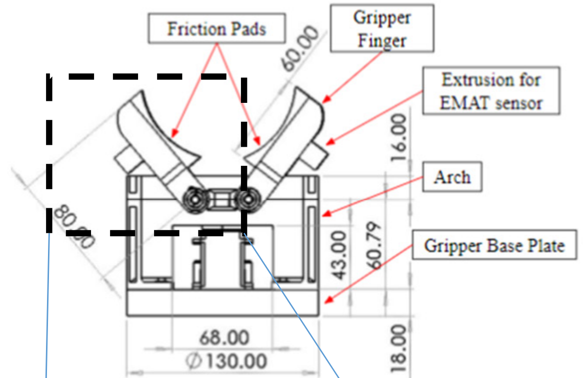
## Electromagnetic acoustic transducer (EMAT) integration

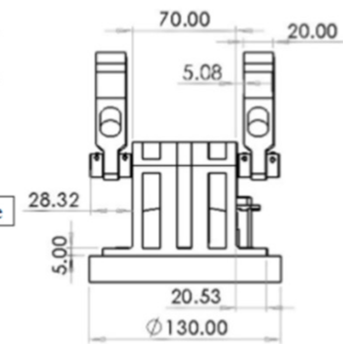
**designed coil**

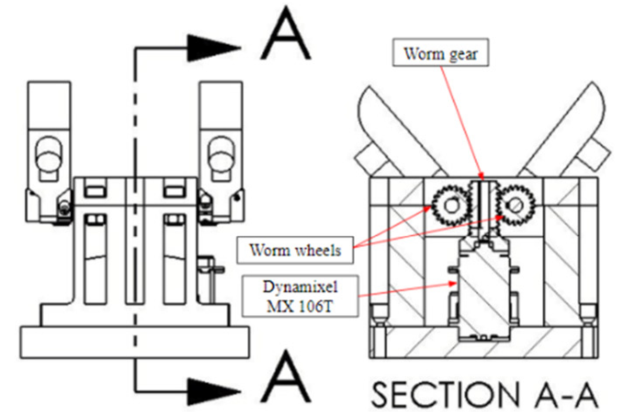


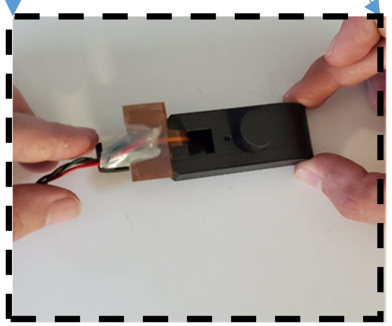

(a) (b) (c)

| | | |
|---|---|---|
| Part Number | | 205C0639 / 205C0034 (for CL) |
| Connector | | 2 Pin Lemo 0B |
| Coil Function | | Transmitter and Receiver |
| Compatible Magnet | | 274A0244, 274A0107 & 274A0144 |
| Coil Geometry | | Spiral |
| Tuning Module[1] | | See Below |
| OD | inch | 0.5 |
| | mm | 12.7 |
| ID | inch | 0 |
| | mm | 0 |

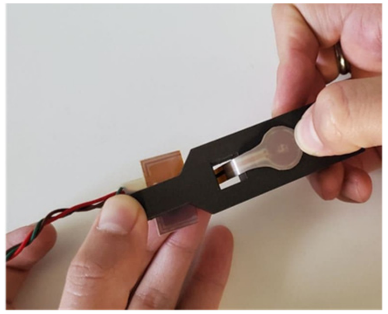


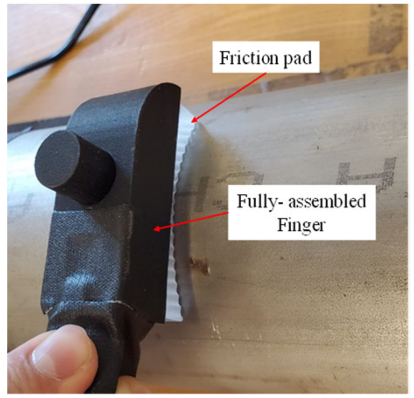



(a)

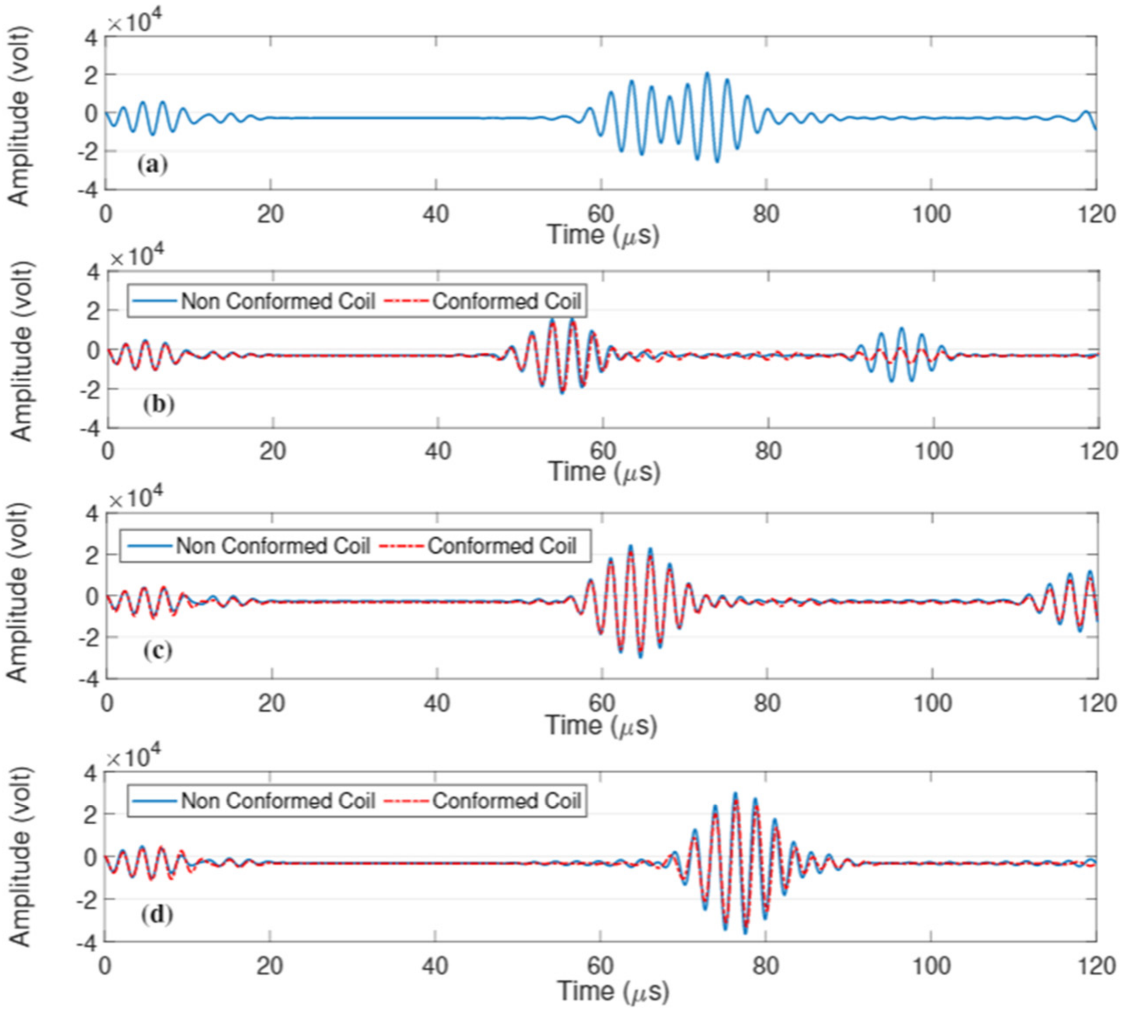


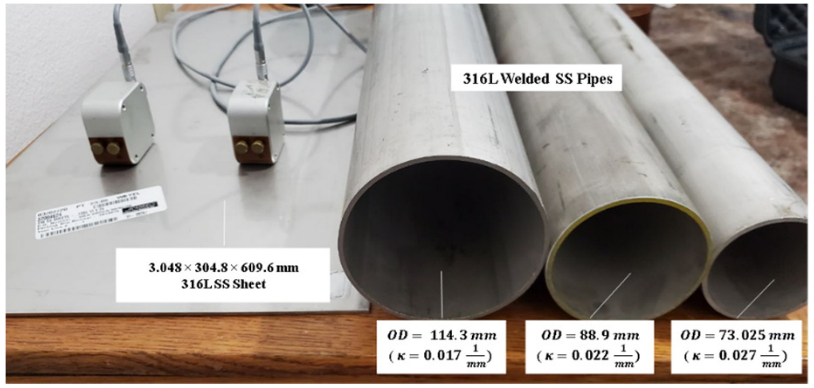
(b)

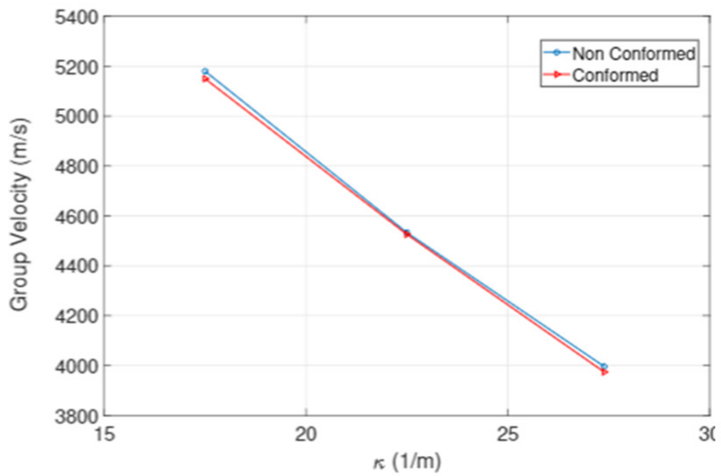


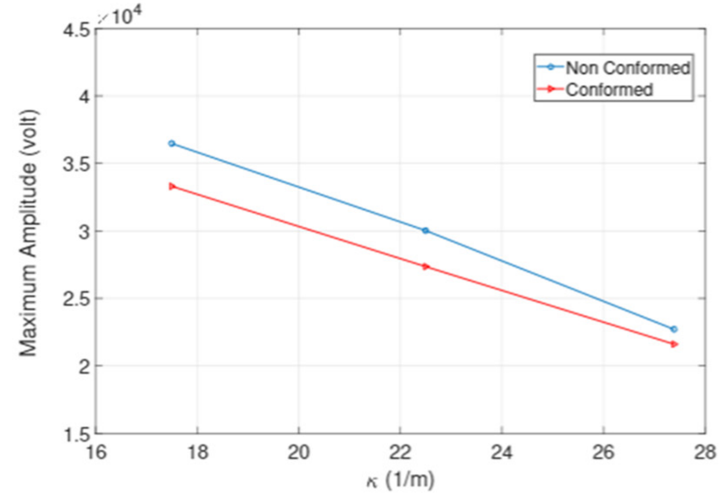
# Couplant-free ultrasound generation

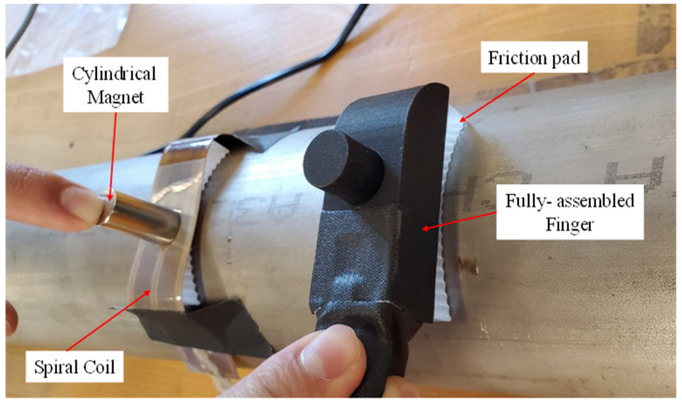
## EMAT Lift-off and curvature effects



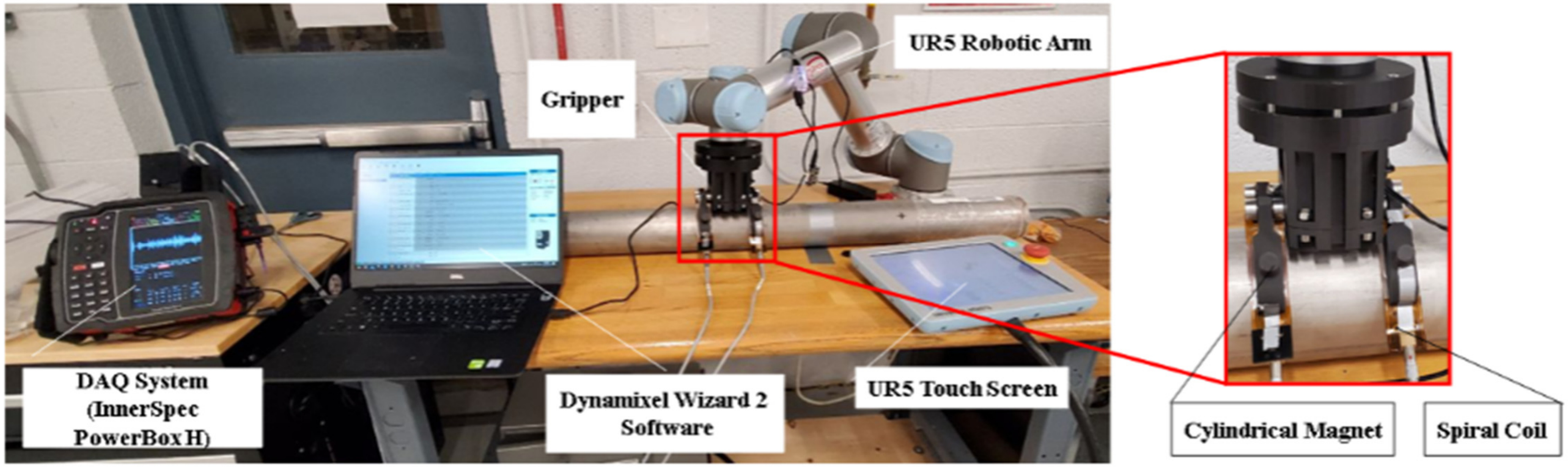



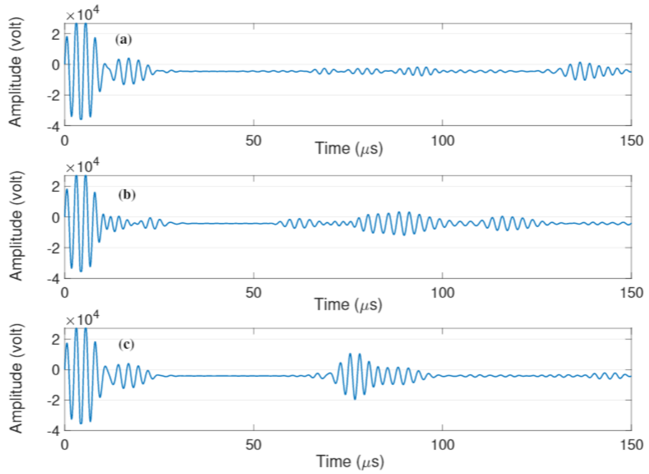

**For dimeter larger than 3" the 1mm lift-off resulted in acceptable SNR**

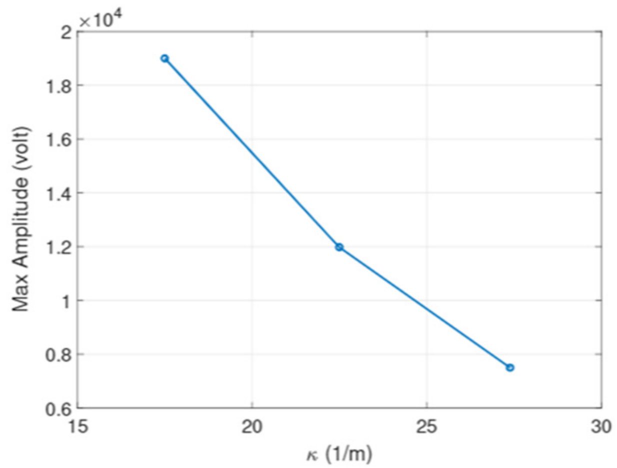
# Couplant-free ultrasound generation

## Integrated gripper and EMATs in motion





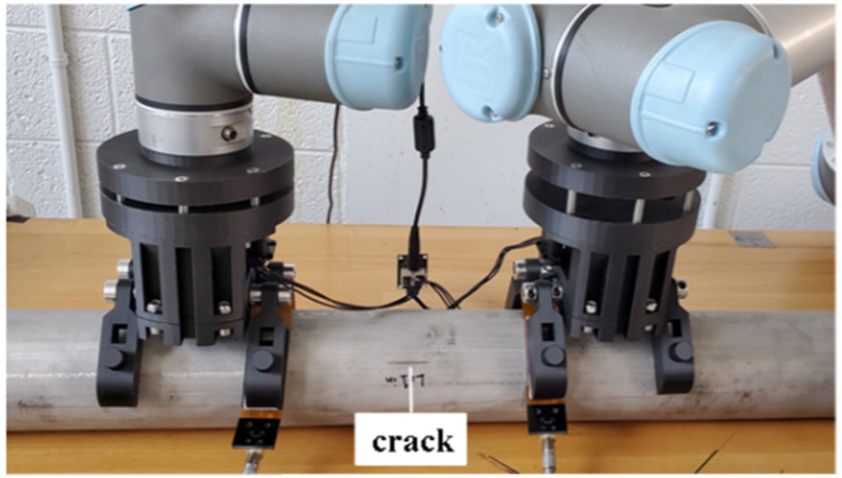


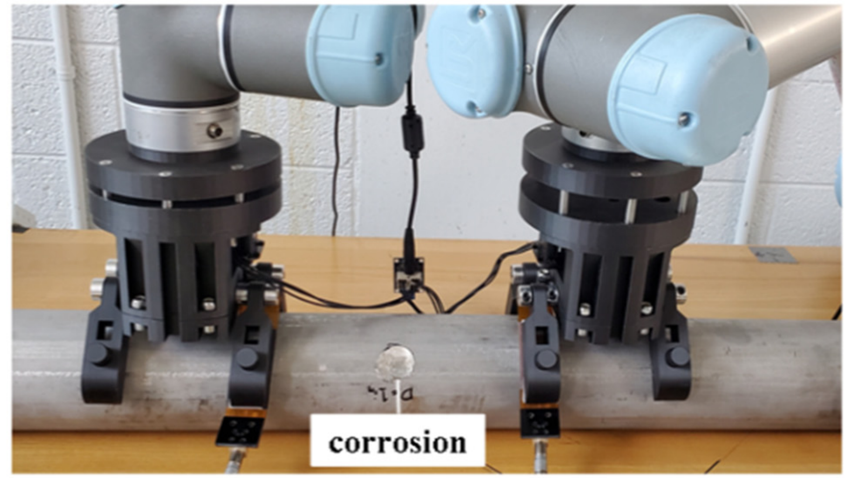



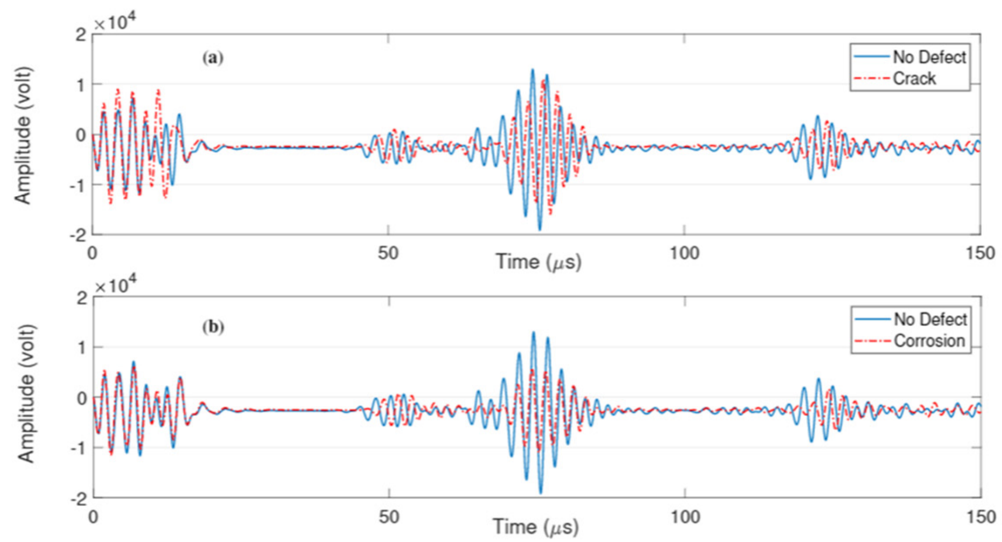

**For dimeter larger than 3" the 1mm lift-off in-motion resulted in an acceptable SNR**

# Couplant-free ultrasound generation

## Simulated Corrosion and Crack



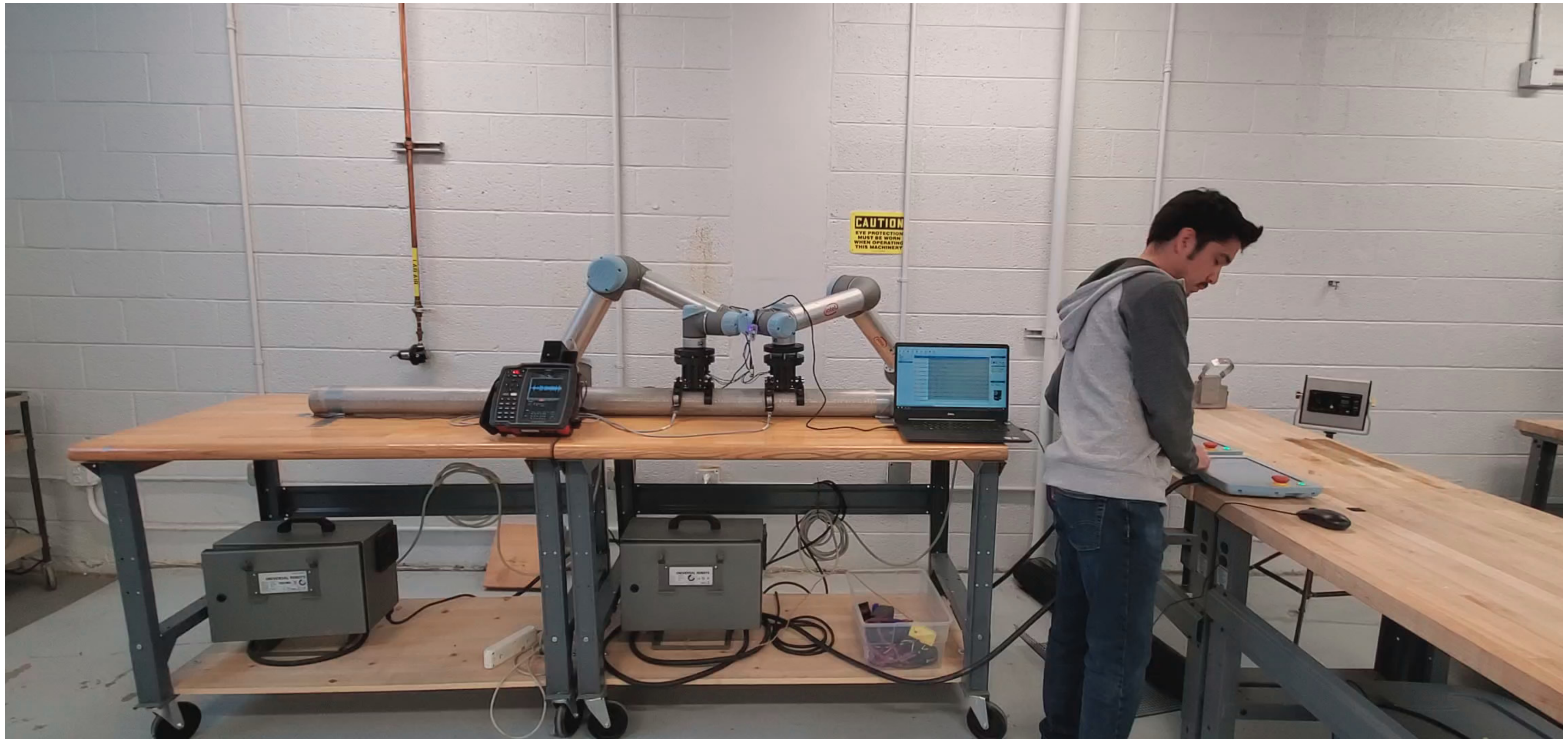



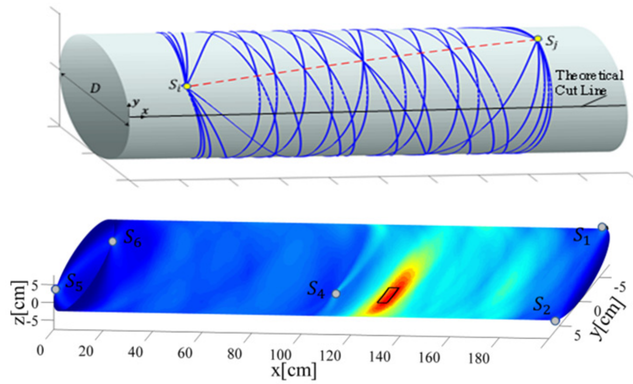

**Amplitude and wave velocity are two effective damage sensitive features for the current design and the simulated defects**

# Couplant-free ultrasound generation

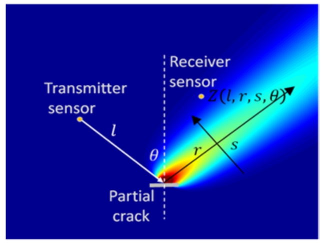
## Lamb wave imaging




MHUI




TFM

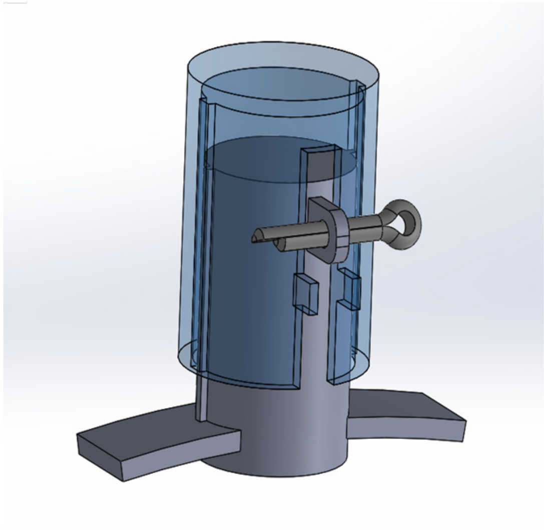


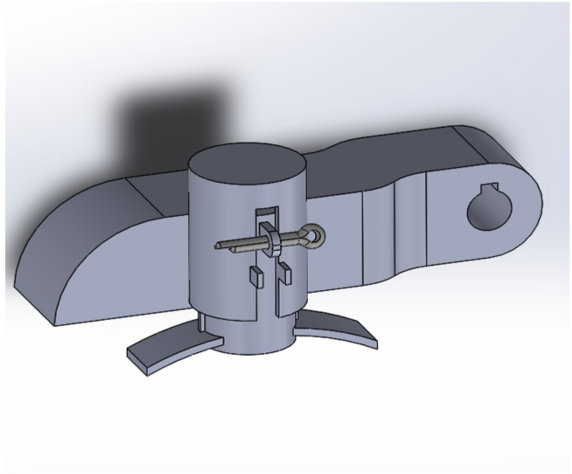

**E. Dehghan-Niri**, S. Salamone, "A Multi-helical ultrasonic imaging approach for the structural health monitoring of cylindrical structures", *Structural Health Monitoring: International Journal, vol. 14 no. 1, pp. 73-85, 2015.*

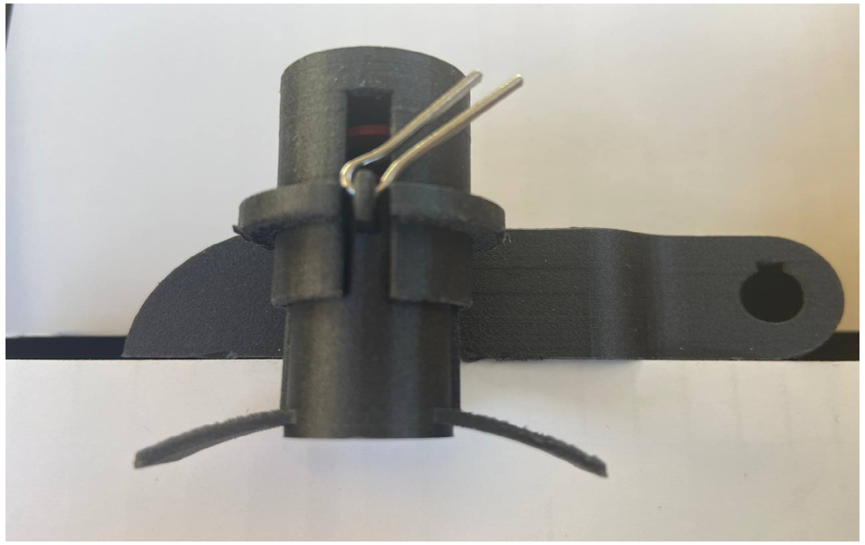
**E. Dehghan-Niri**, S. Salamone, "*Quantitative Corrosion Imaging of Pipelines using Multi-Helical Guided Ultrasonic Waves*", *Structural Monitoring and Maintenance, An international Journal, Vol. 3, No. 3, pp. 215-232, 2016.*

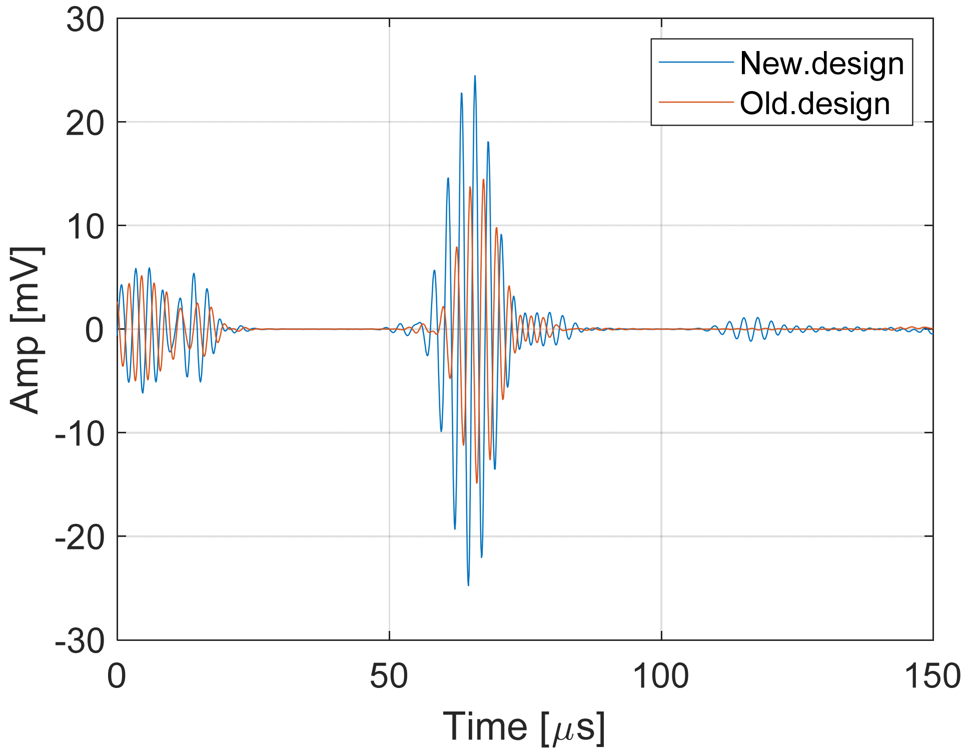
**Lamb wave based imaging is in progress**

# New finger design



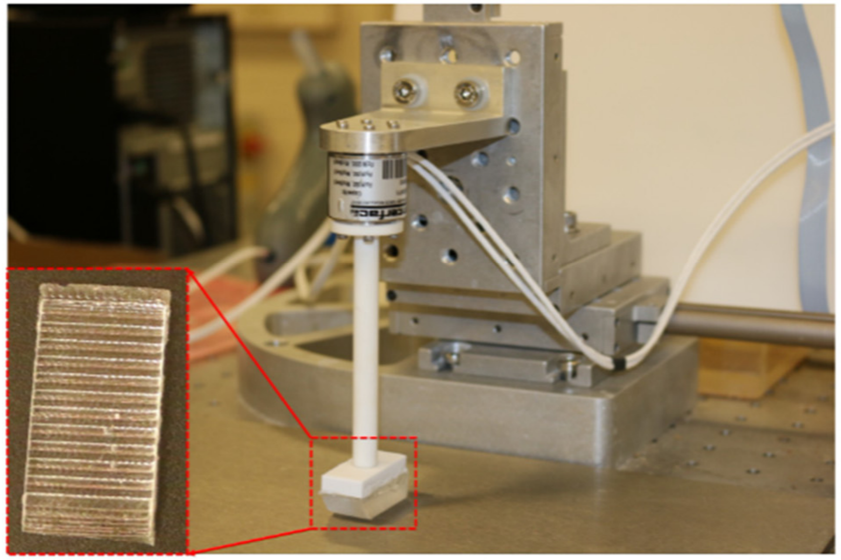


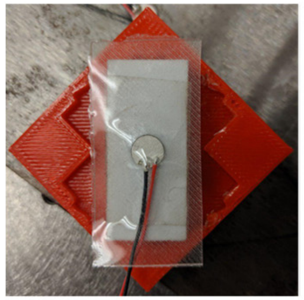


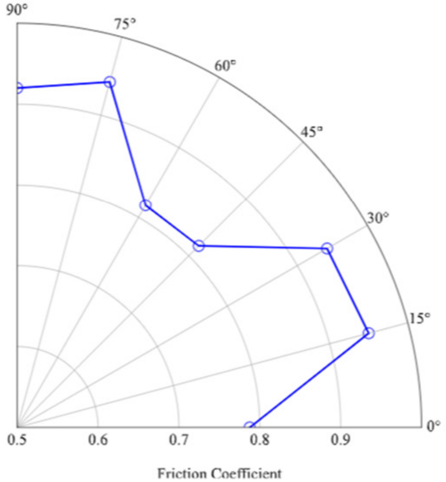


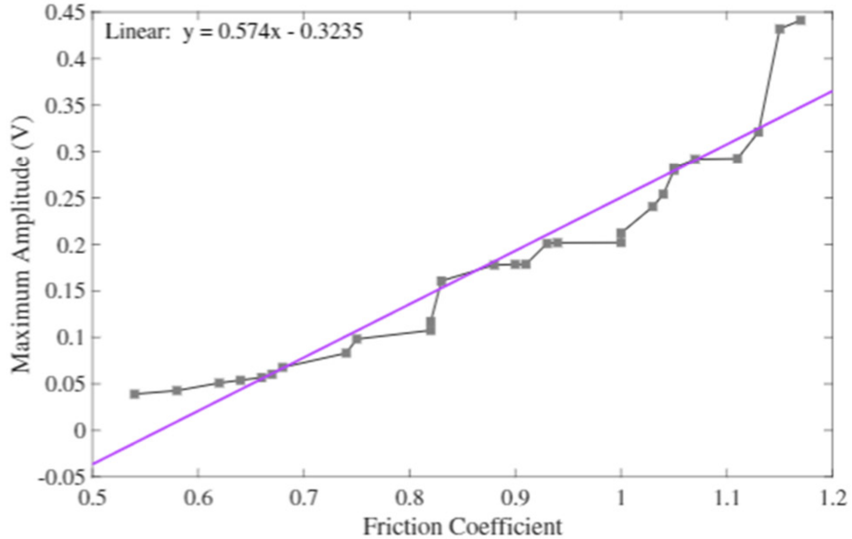
# Couplant-free ultrasound generation

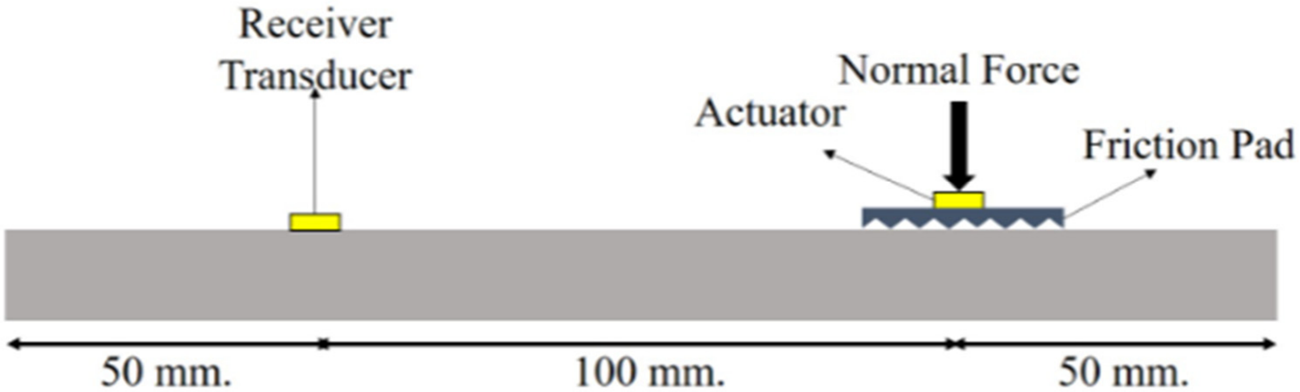
## Friction based Lamb waves







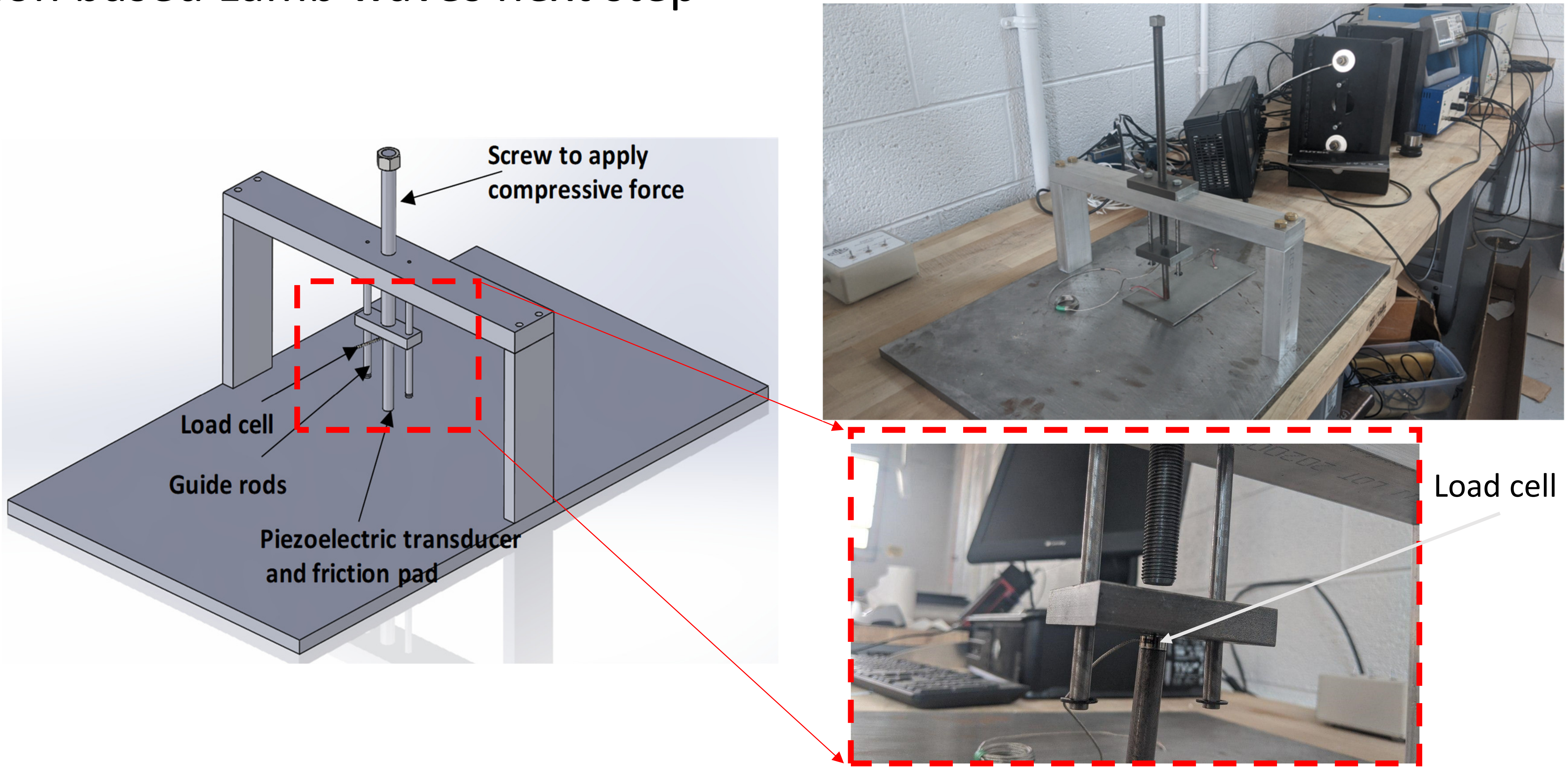



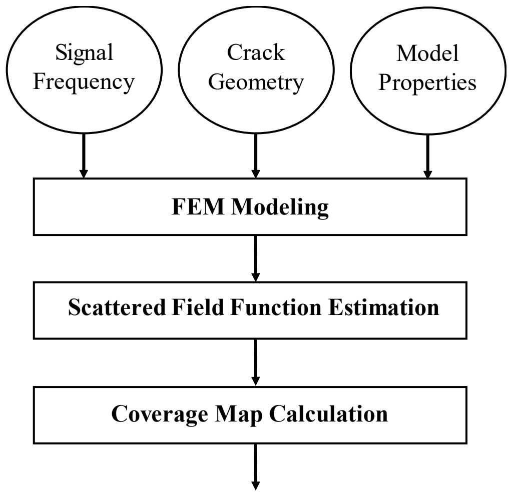

SNR has a linear relationship with friction coefficient

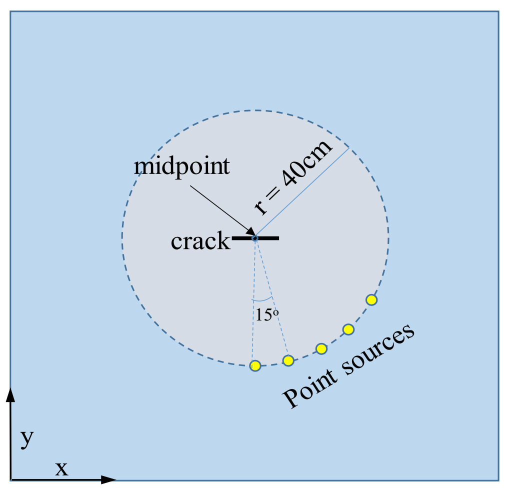
# Couplant-free ultrasound generation

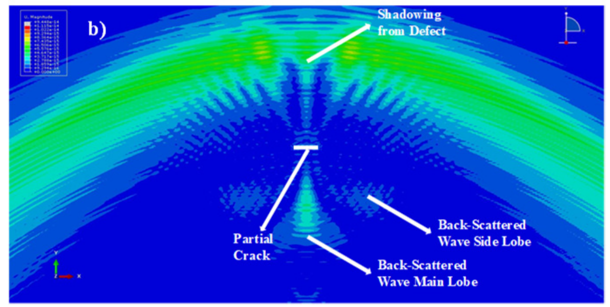
## Friction based Lamb waves next step

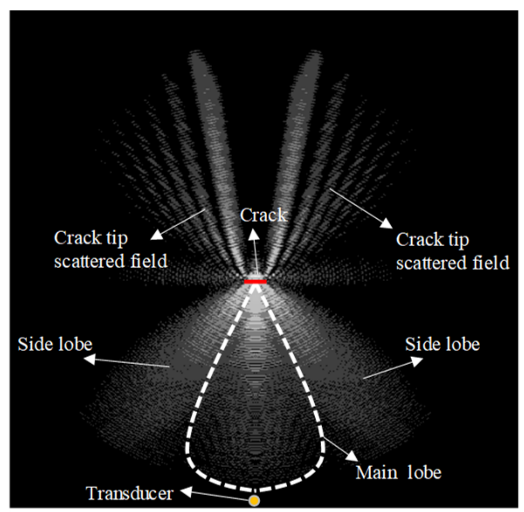


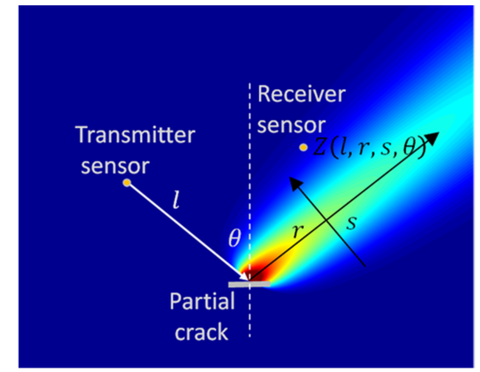
# Crack detection



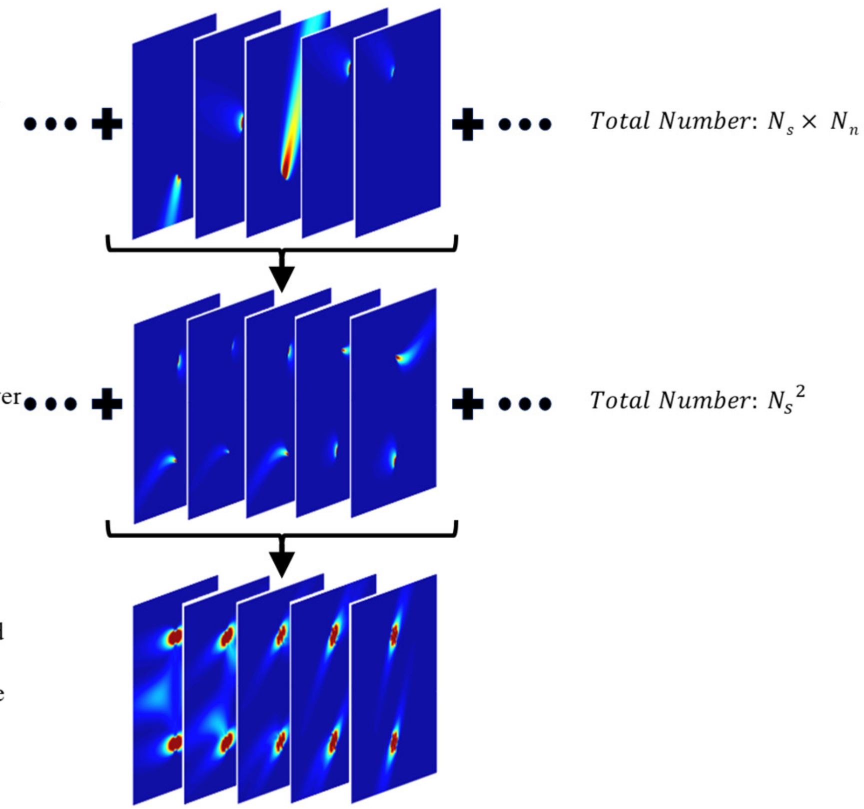



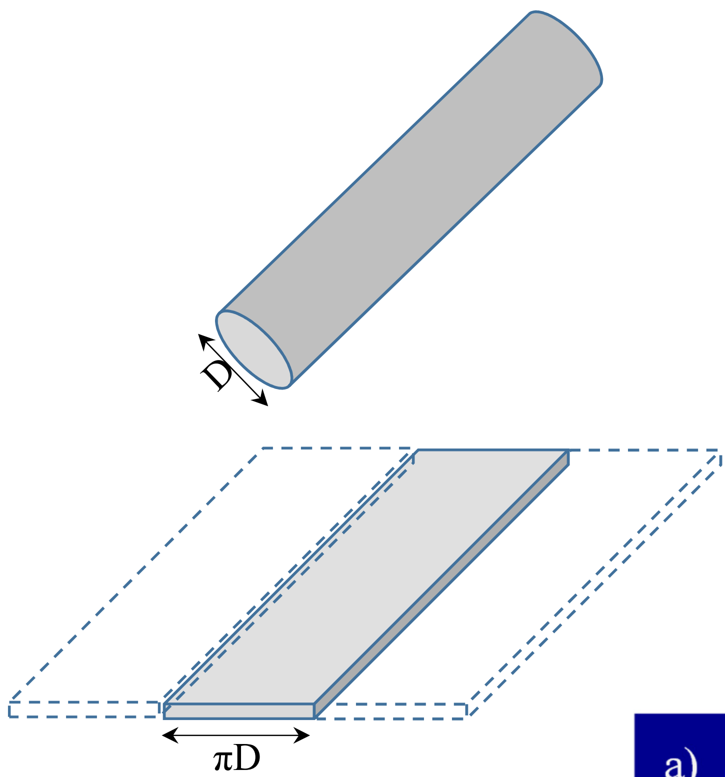

Estimated scattered field for crack-transducer combinations (eq. 5) at each gridded location

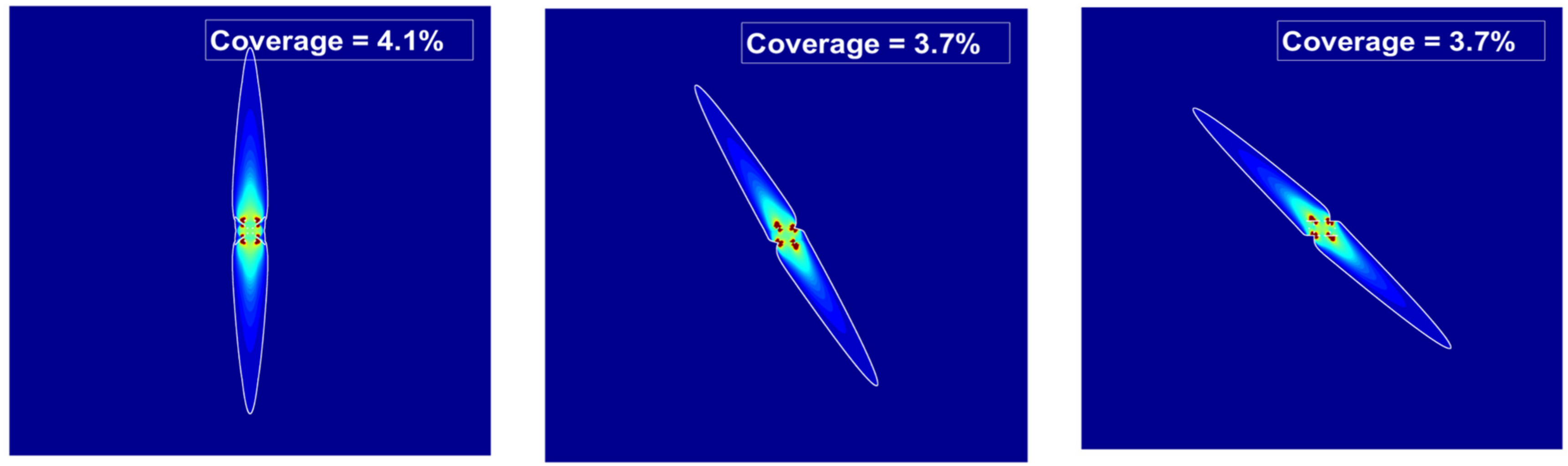
Coverage area for each pair of transducer-receiver combinations (eq. 6)

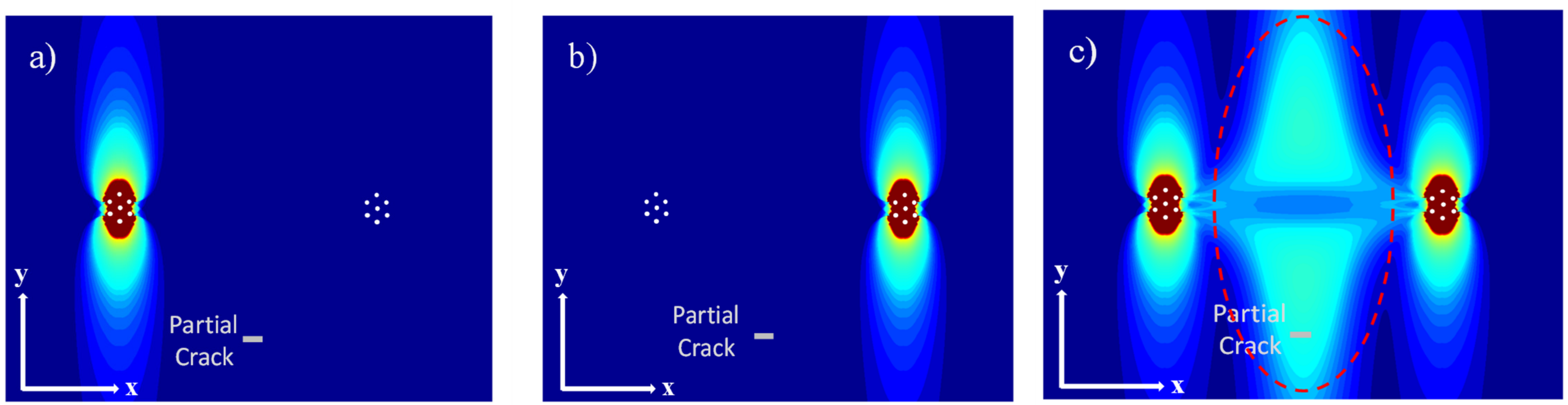
Superposition of the results from all pairs and crack location combinations to estimate coverage of the sensor network



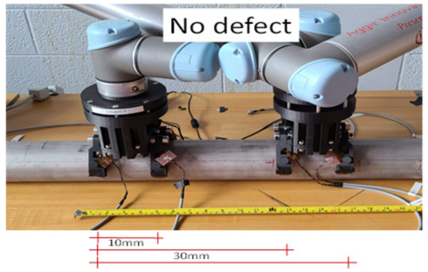
# Coverage Prediction of moving sensor network

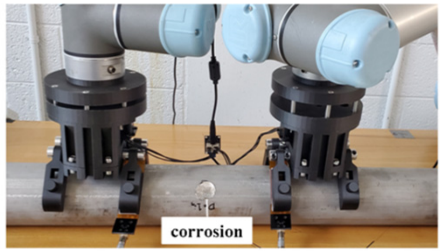


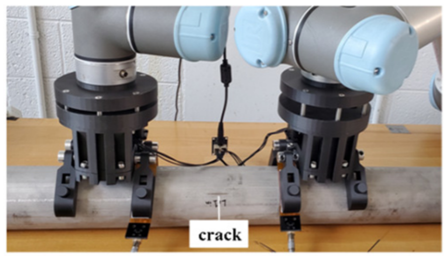



# DL enabled defect detection



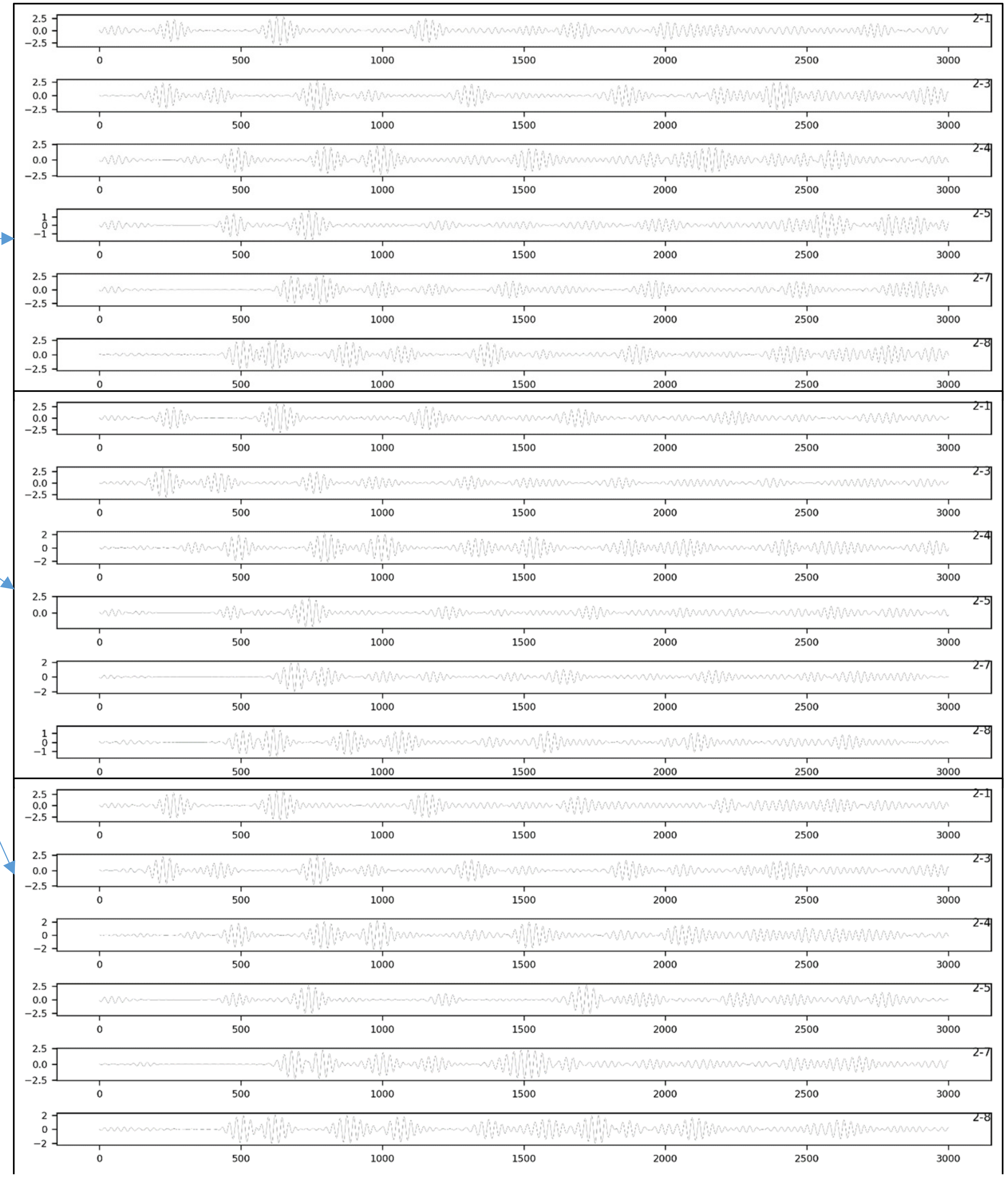



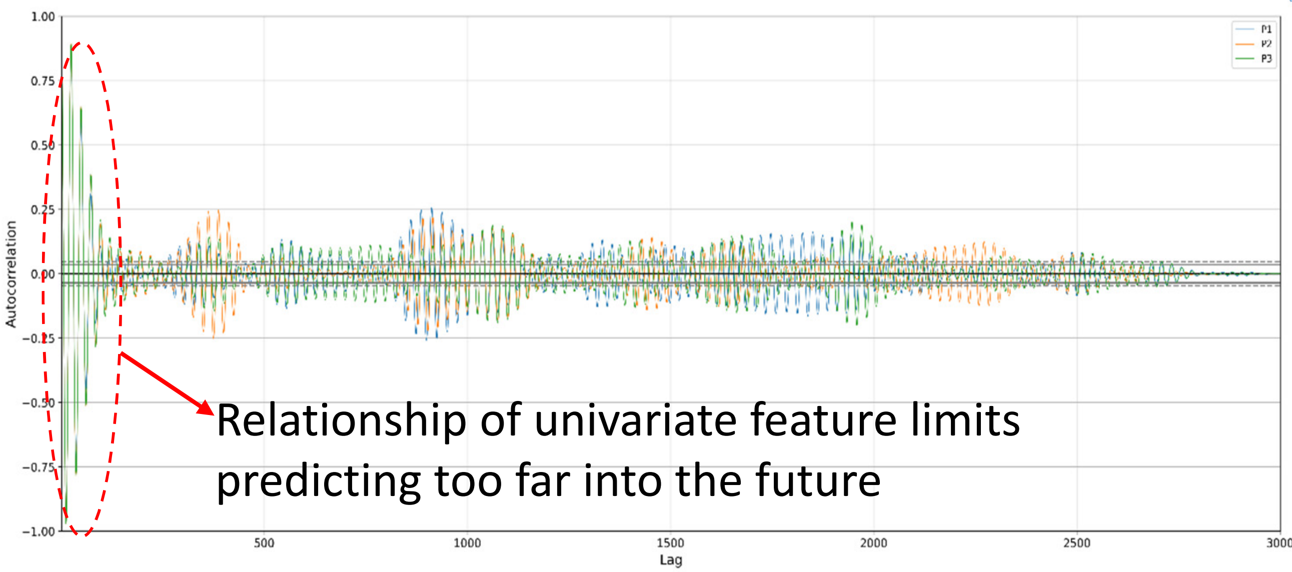

Raw data

No defect
Label-0

Corrosion
Label-1

Crack
Label-1



# DL enabled defect detection

- Long-short term memory (LSTM)
  - Can be utilized for univariate TSC, Promising candidate for robotic inspection (sequence classification)
  - Training: stochastic gradient descent with momentum
  - ADAM

$$f_t = \sigma(W_{fh}h_{t-1} + W_{fx}x_t + b_f)$$

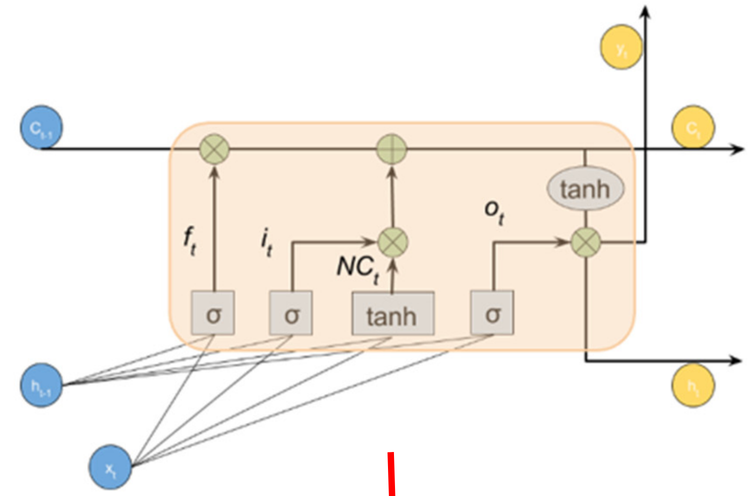
$$i_t = \sigma(W_{ih}h_{t-1} + W_{ix}x_t + b_i)$$

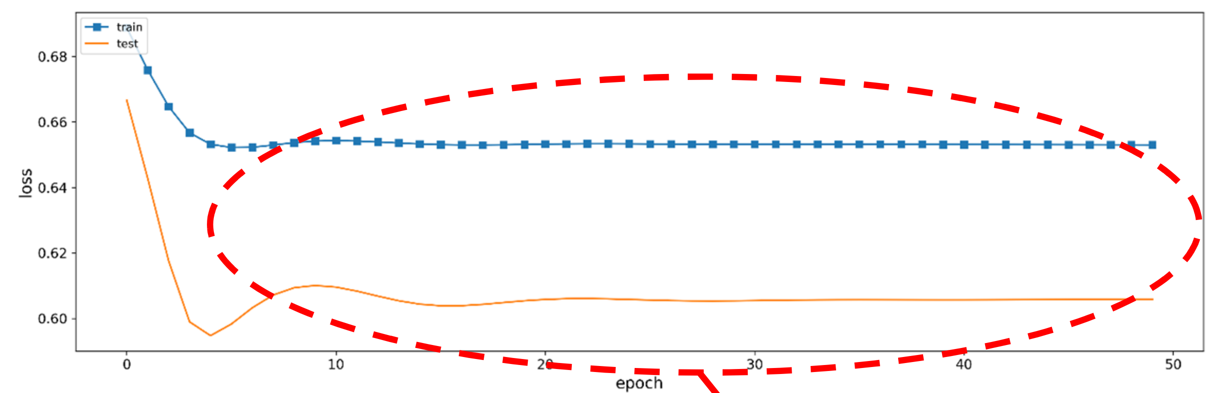
$$C_t = f_t \cdot c_{t-1} + i_t \cdot NC_t$$

$$NC_t = \tanh(W_{NC_t h}h_{t-1} + W_{NC_t x}x_t + b_{NC_t})$$

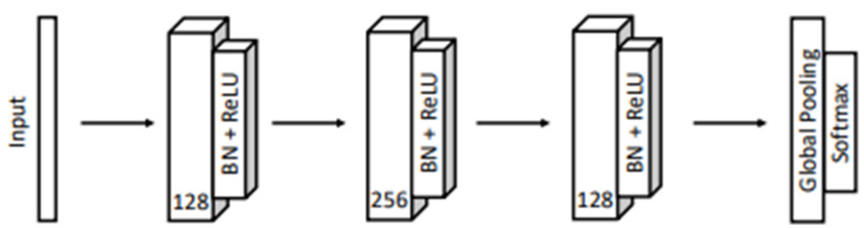
$$o_t = \sigma(W_{oh}h_{t-1} + W_{ox}x_t + b_o)$$

$$h_t = o_t \cdot \tanh(c_t)$$




- Fully Convolutional Network (FCN)
  - $y = W \otimes x + b$




FCN Structure

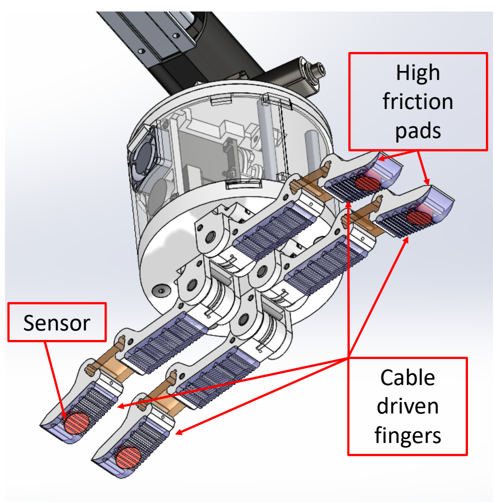
| Model | Classification (%) |
|---|---|
| Vanilla LSTM | **73.81** |
| FCN | 21.43 |

Preliminary Results

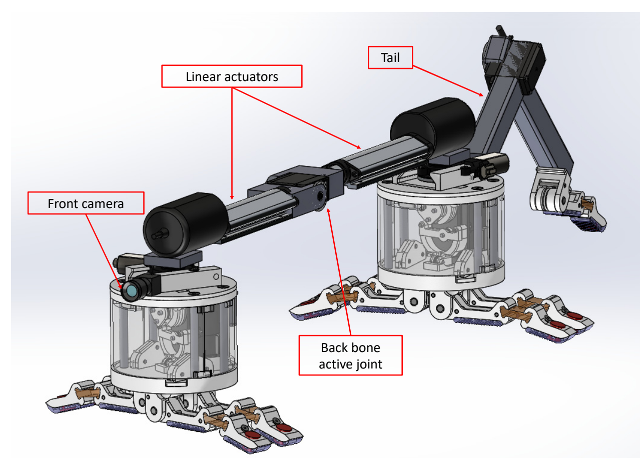
Opportunity to improve training with LSTM

# LTI Robot

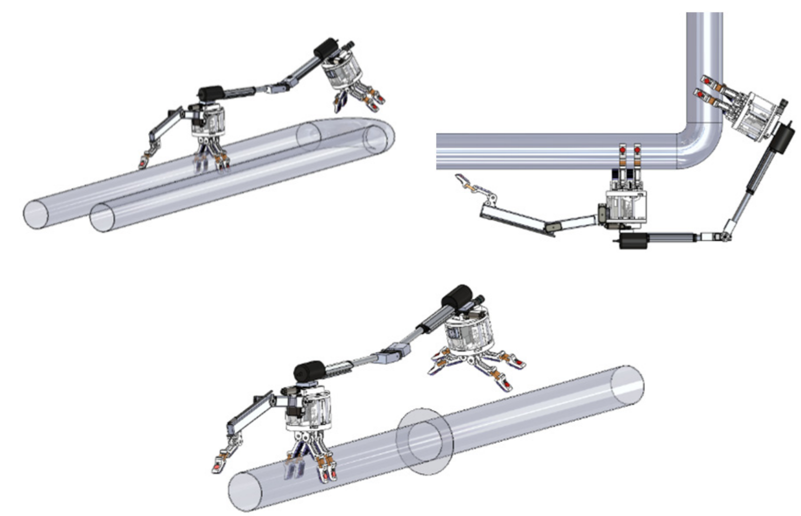
**Multifunctional Gripper**




**Main Body**

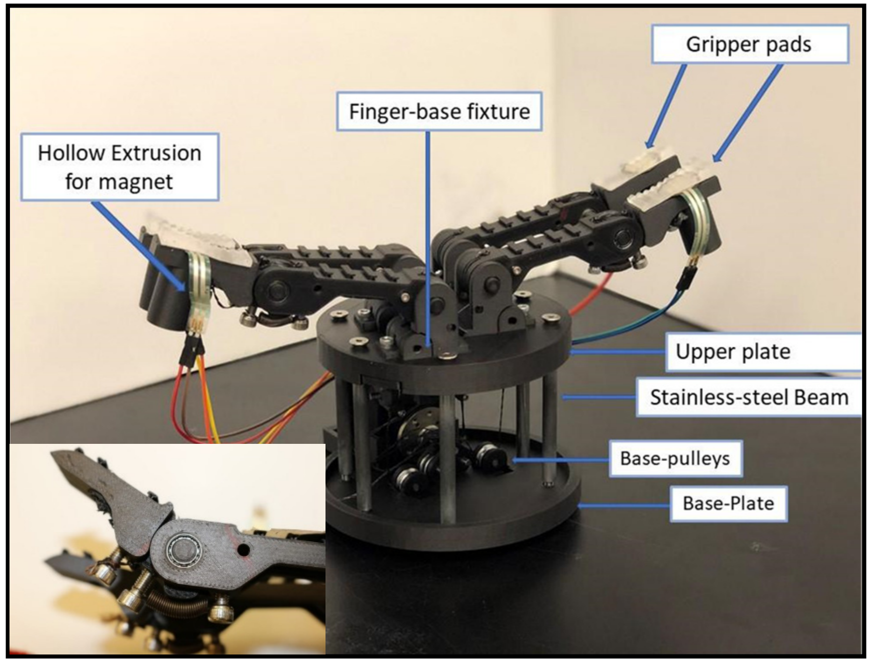


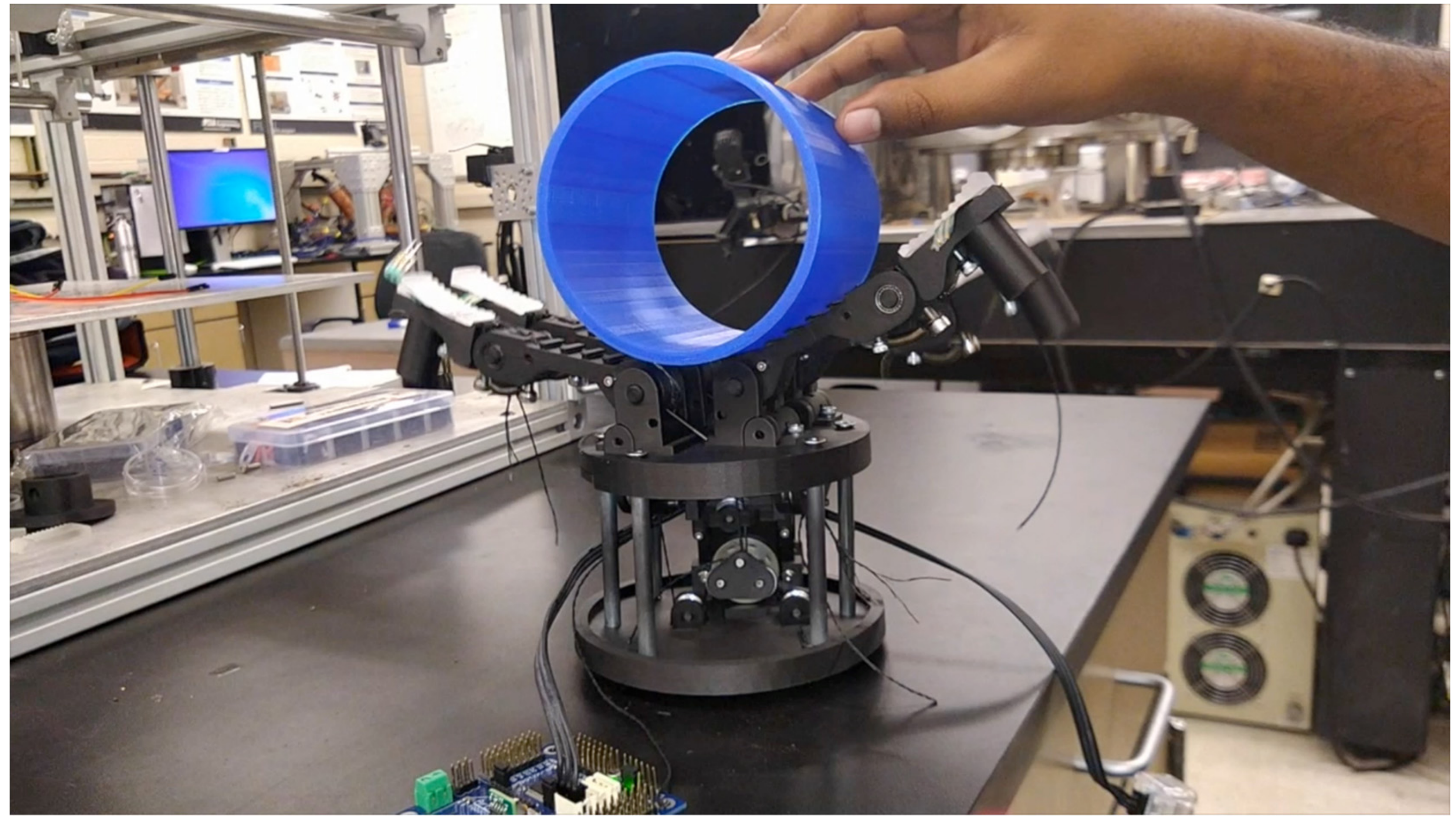

**Experimentation**



# Multifunctional Gripper

## Original Design (v1)



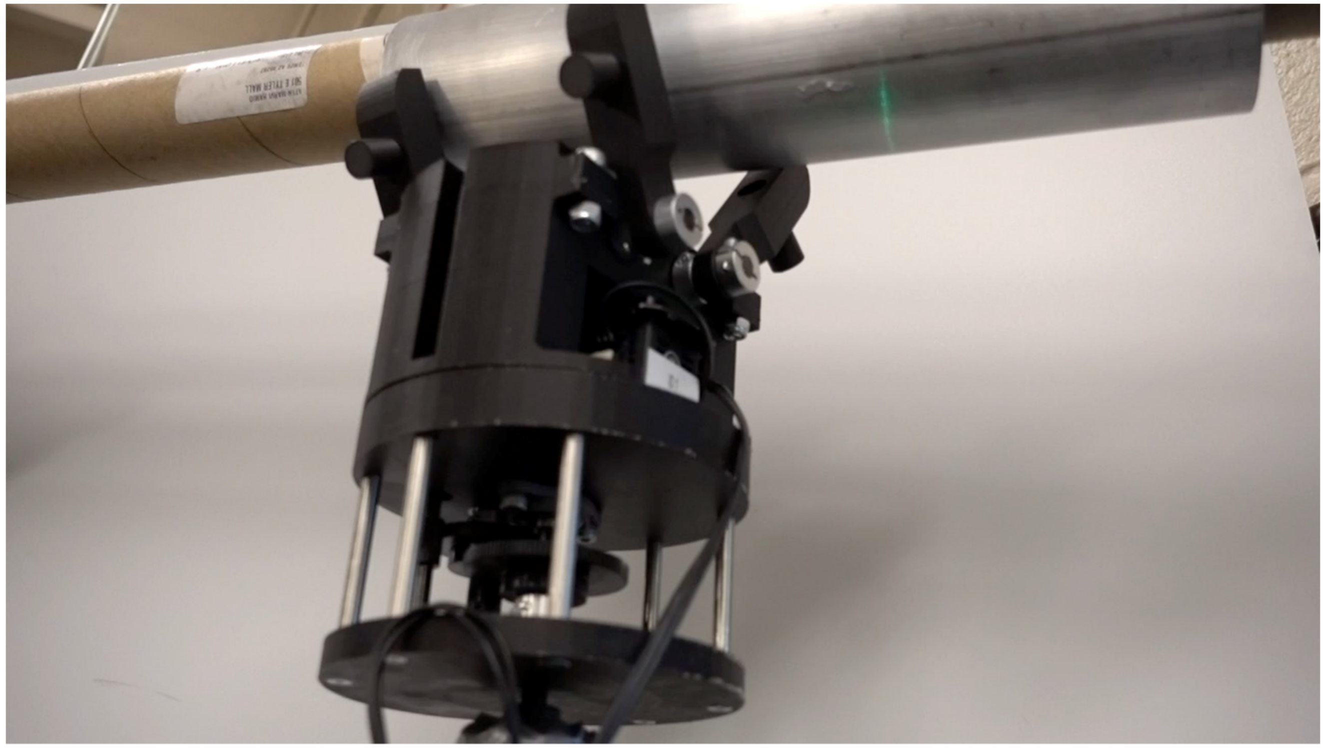
- This design was an upgrade to the Yale open-ended gripper design (Kevlar strings and pulleys).

- The kevlar strings tend to snap or lose their tension after multiple actuations of the gripper.

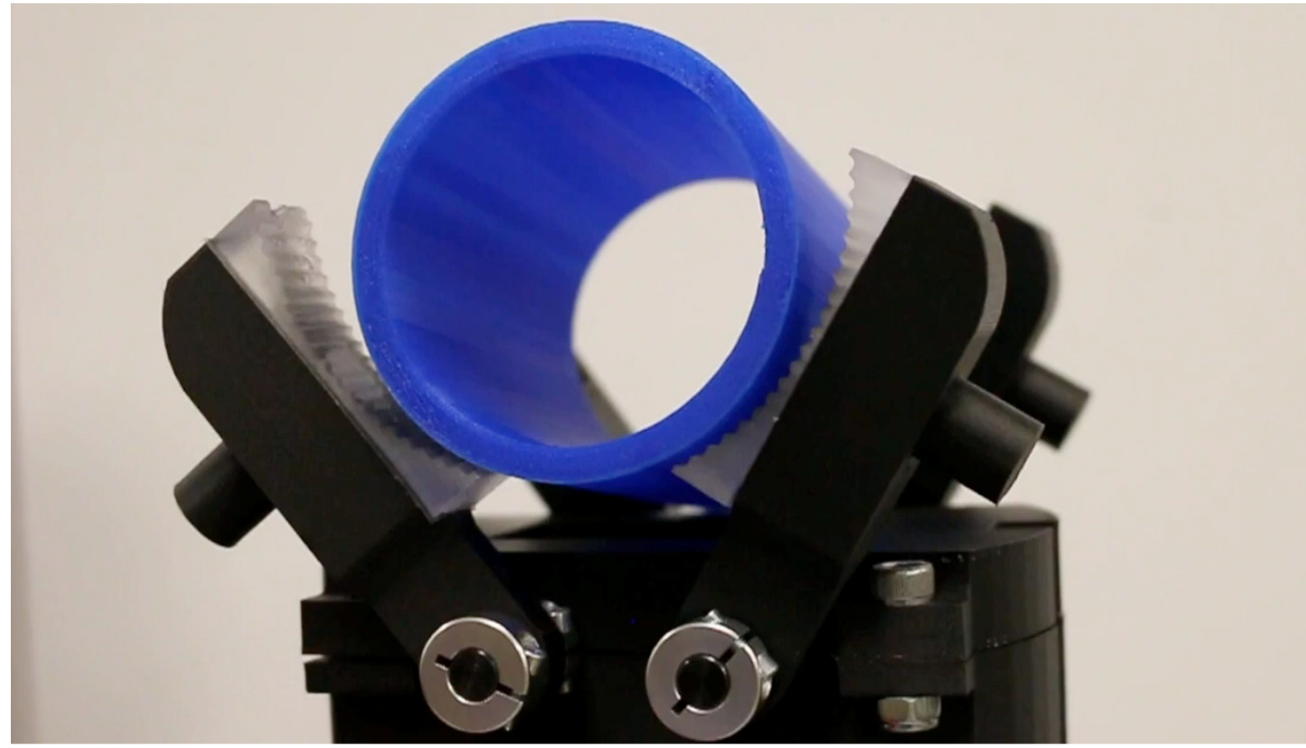
- The gripper can provide relatively small normal load

# Multifunctional Gripper

## New Design (v2)



Video sped up 4 times

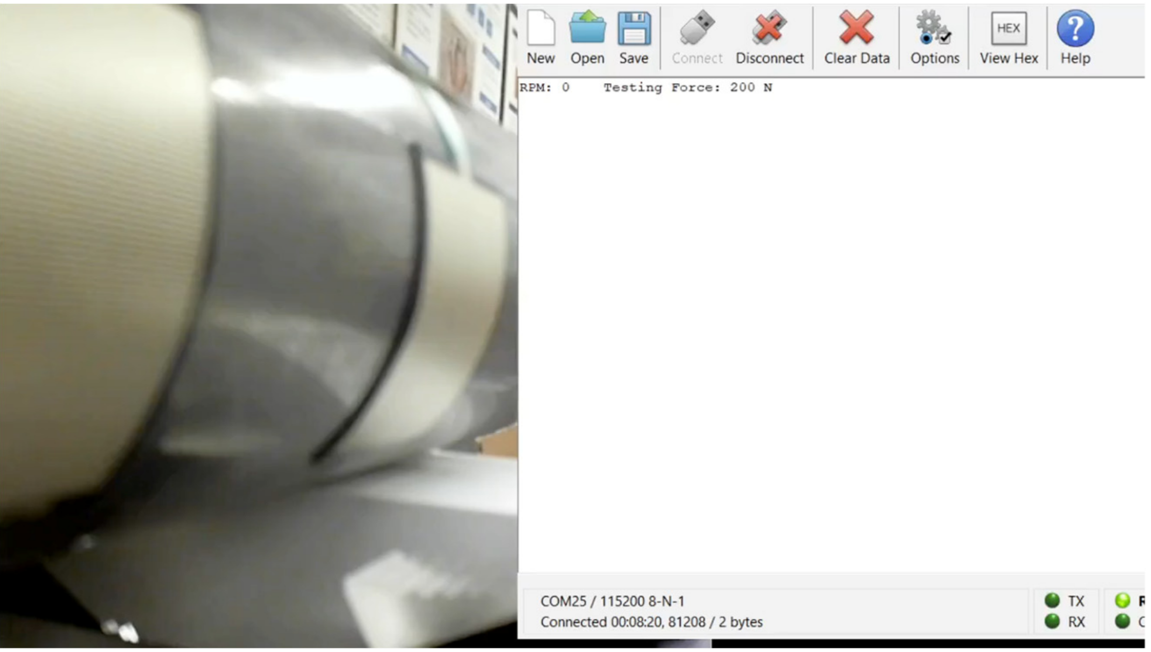


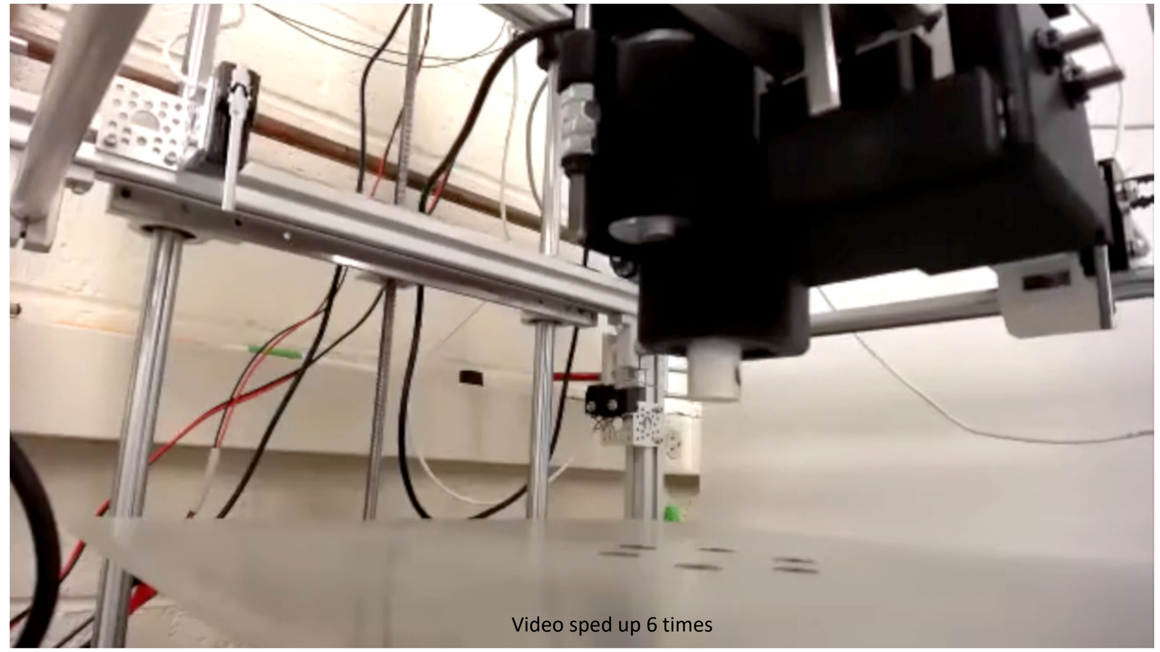
Video sped up 8 times

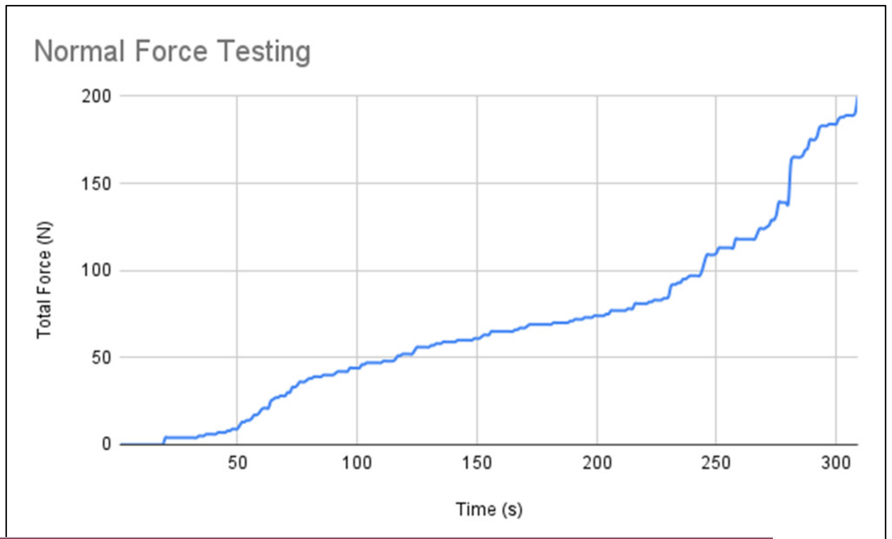
- The actuation mechanism of kevlar strings was replaced by a worm gear pair with a gear ratio of 1:10 to ensure a robust and stable actuation of the gripper.

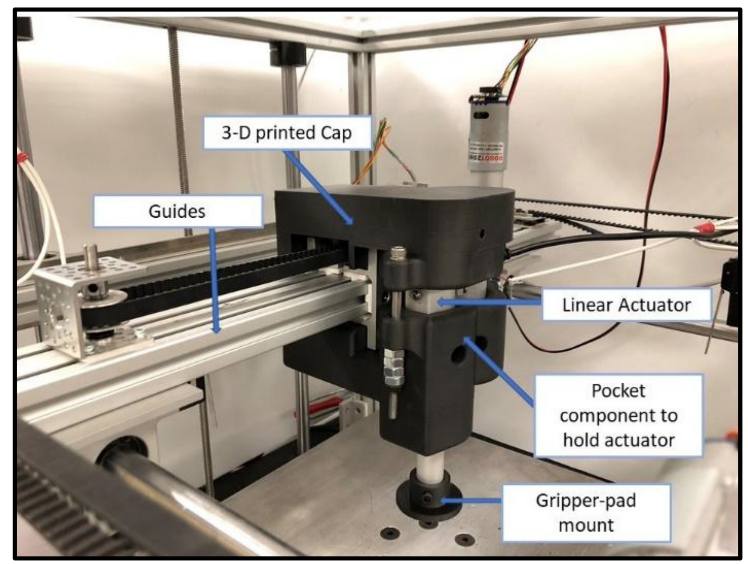
- The normal load was increased by two orders of magnitude compared to v1

# Normal Load and Friction characterization

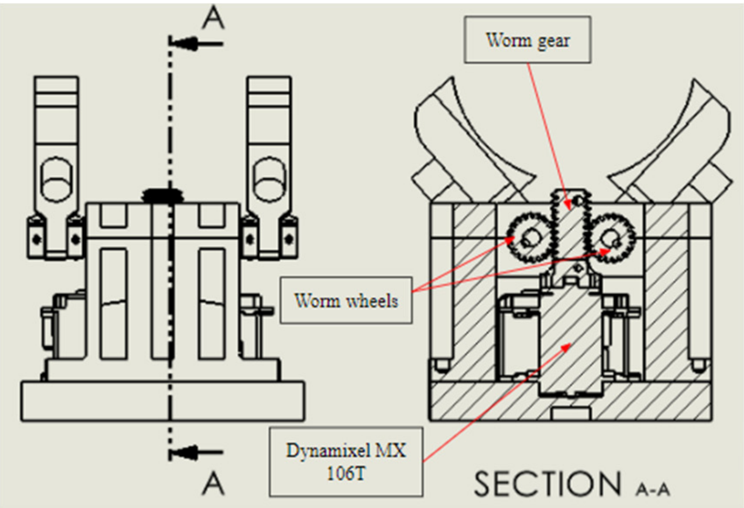


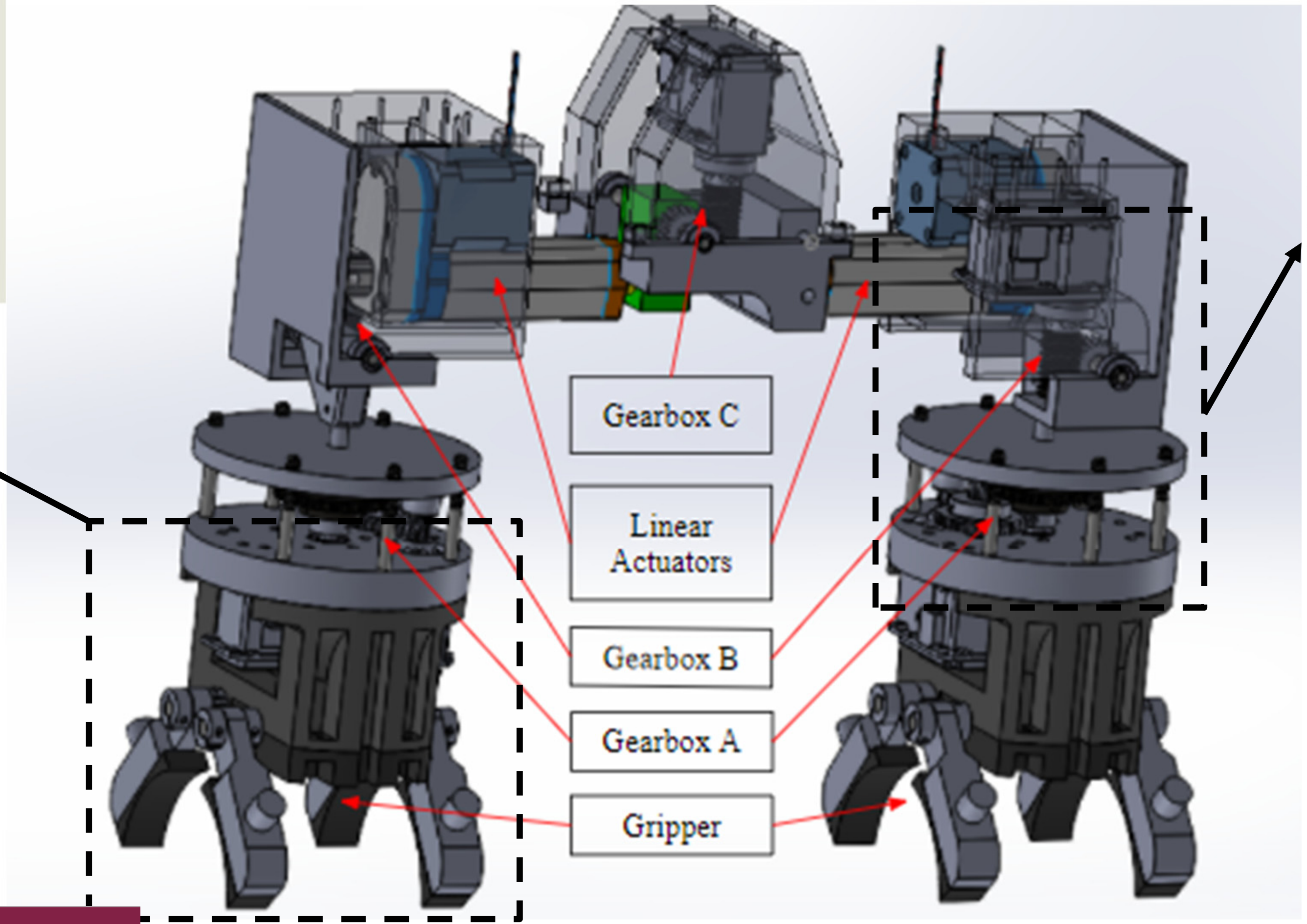



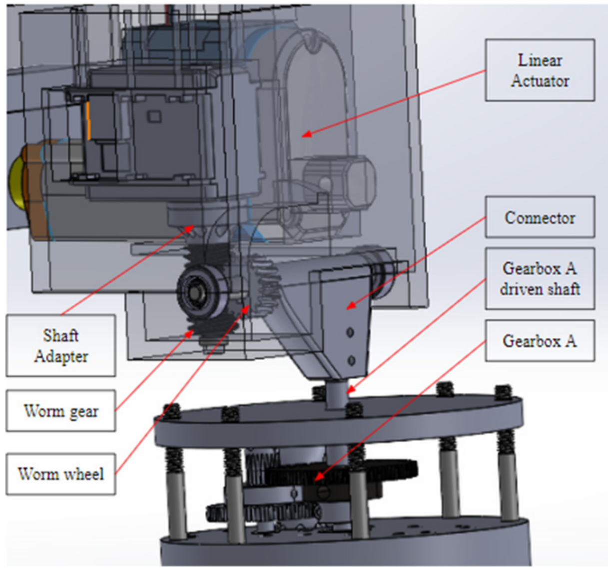



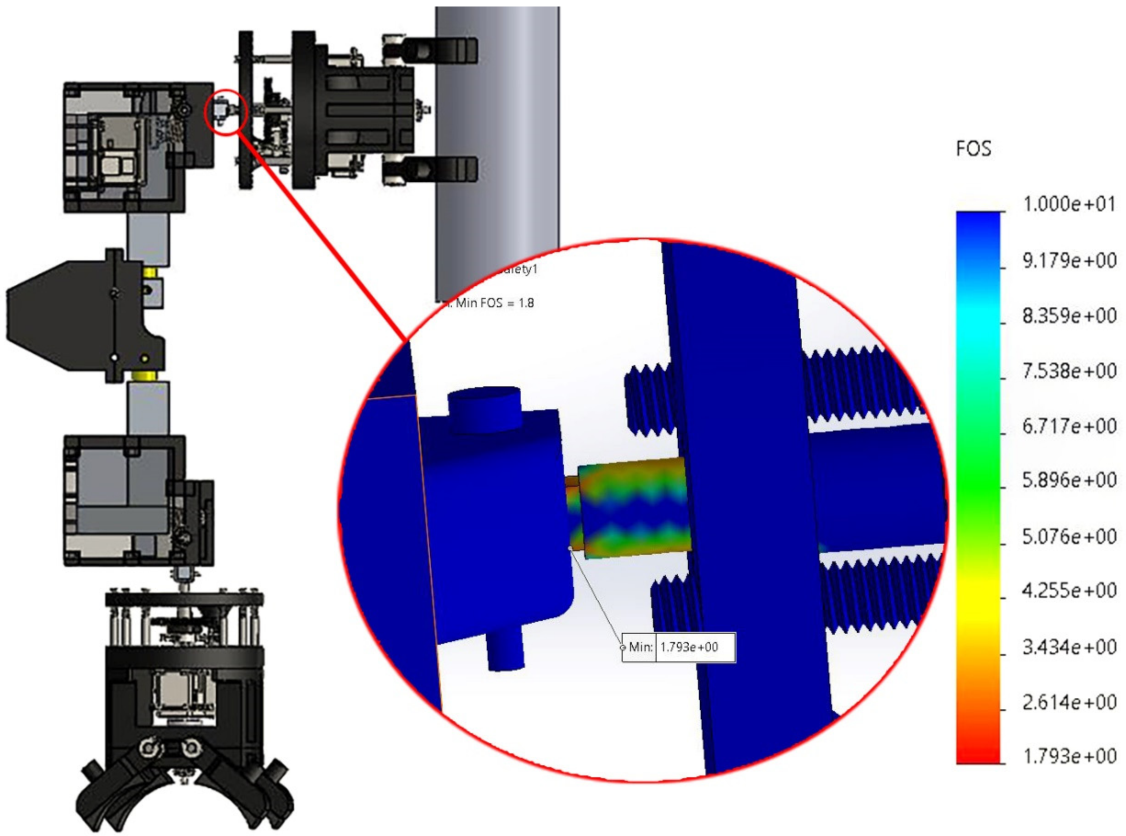
# Main body of the LTI robot

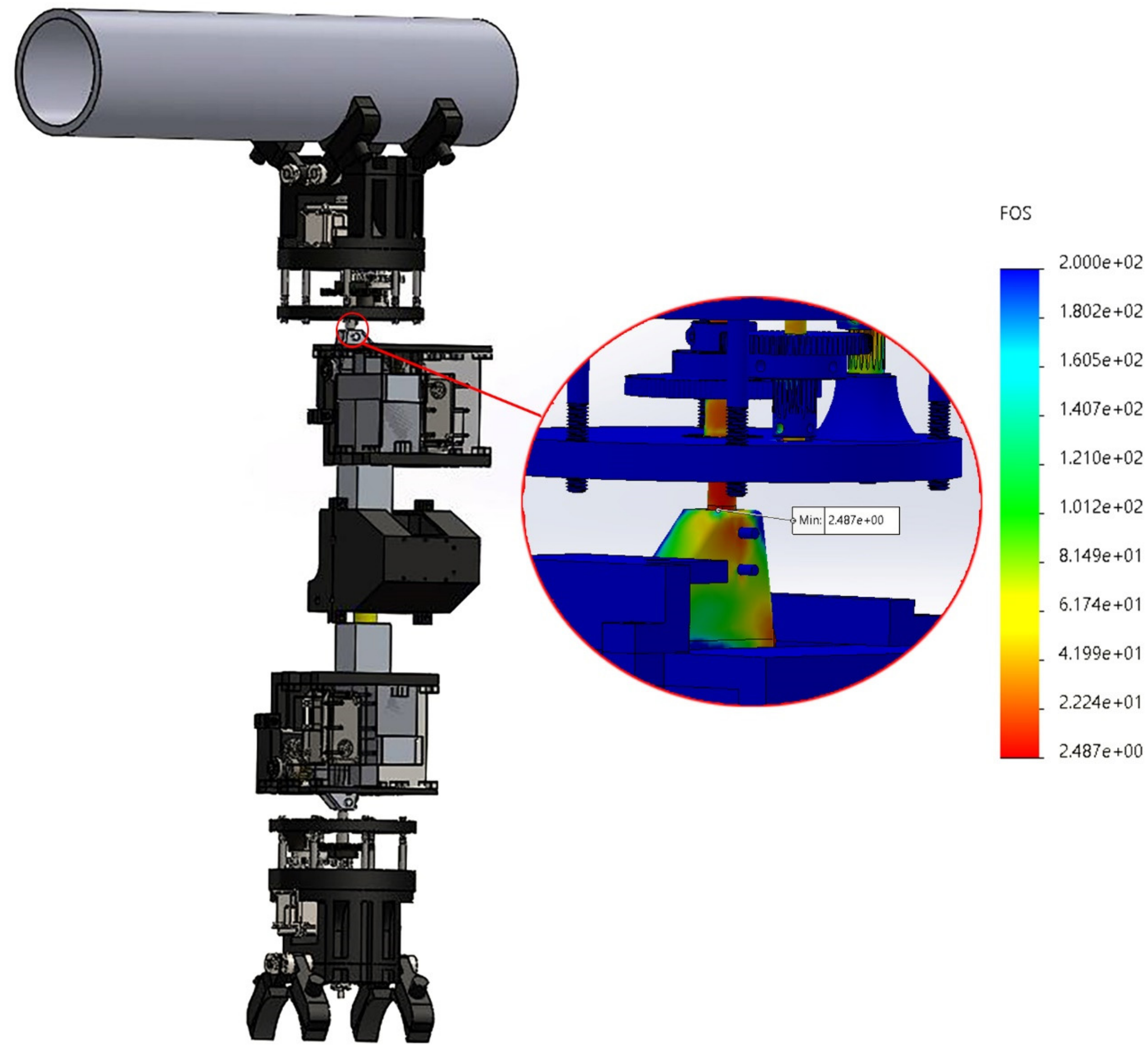


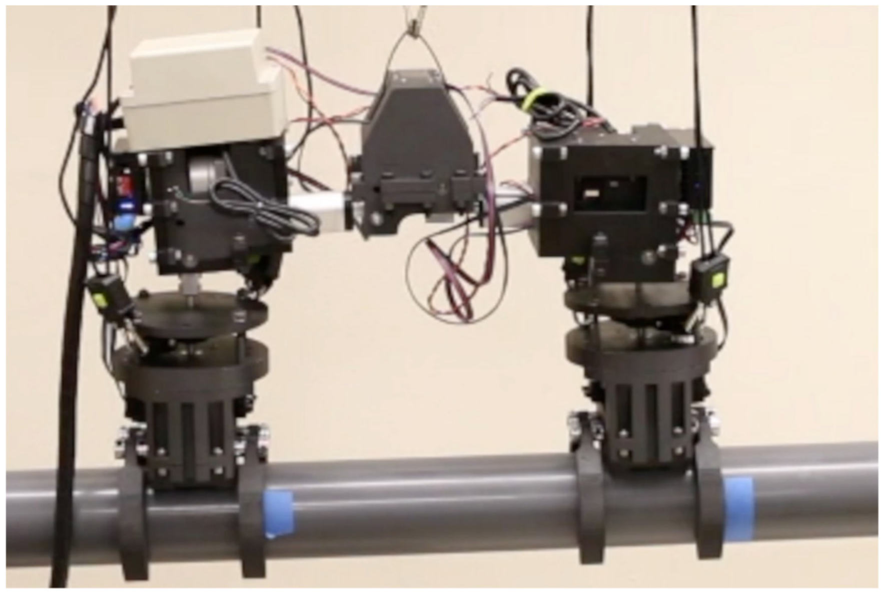



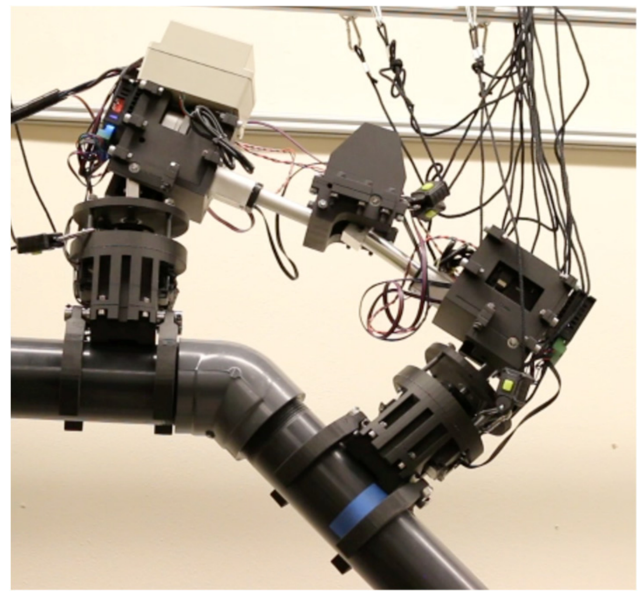
# Finite Element Analysis of the LTI Robot

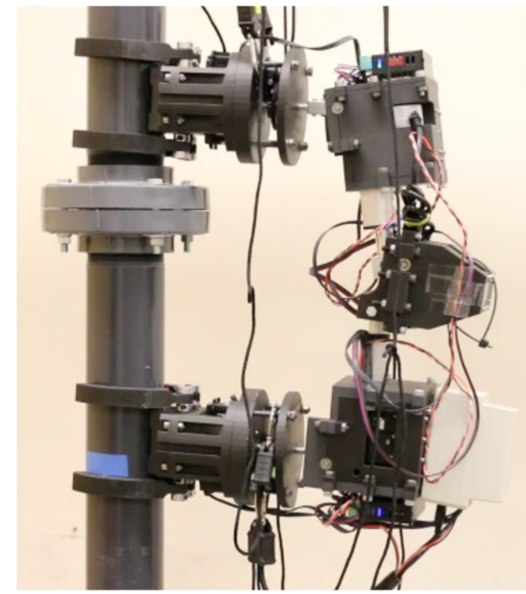


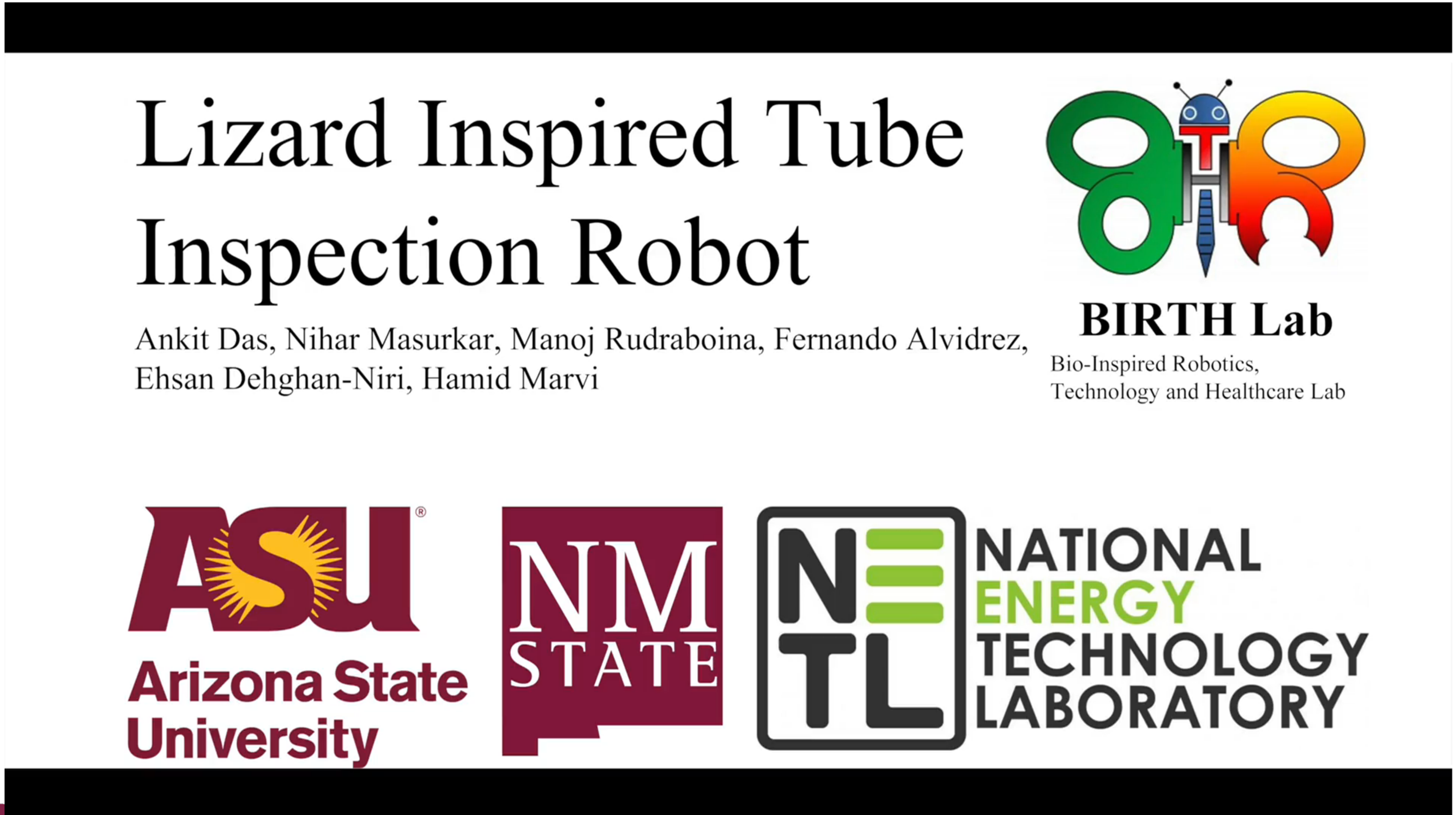
# LTI robot in action







# LTI robot in action




Video sped up 4 times

# Outcomes, publications, patents

## Journals

1. H. Nematia, F. Alvidrez, A. Das, N. Masurkar, M. Rudraboina, H. Marvi, and E. Dehghan-Niri, "Integrating electromagnetic acoustic transducers in a modular robotic gripper for inspecting tubular components" Materials Evaluation, pp. 715-727, 2021
2. M. Ghyabi, H. Nemati and E. Dehghan-Niri, "*A simplified framework for prediction of sensor network coverage in real-time structural health monitoring of plate-like structures*," Structural Health Monitoring: and International Journal, 2021
3. S. Zamen, E. Dehghan-Niri, M. Ilami, V. Anand Senthilkumar, and H. Marvi, "Recurrence analysis of friction based dry-couplant ultrasonic Lamb waves in plate-like structures", Ultrasonics, Vol. 120, March 2022, 106635.
4. Das, M. Rudraboina, N. Masurkar, F. Alvidrez*, E. Dehghan-Niri, and H. Marvi, "Lizard Inspired Tube Inspection Robot", IEEE Robotics and Automation Letters, under review.

## Thesis

F. Alvidrez, "*INTEGRATING ELECTROMAGNETIC ACOUSTIC TRANSDUCERS IN A MODULAR ROBOTIC GRIPPER FOR INSPECTING TUBULAR COMPONENTS*", NMSU, 2021.

N. Masurkar, "*Design and Control of a Lizard-inspired Tube Inspector Robot*", ASU, 2022.

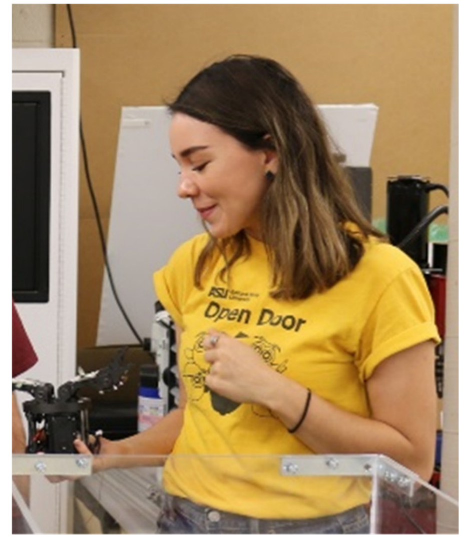
## Patents

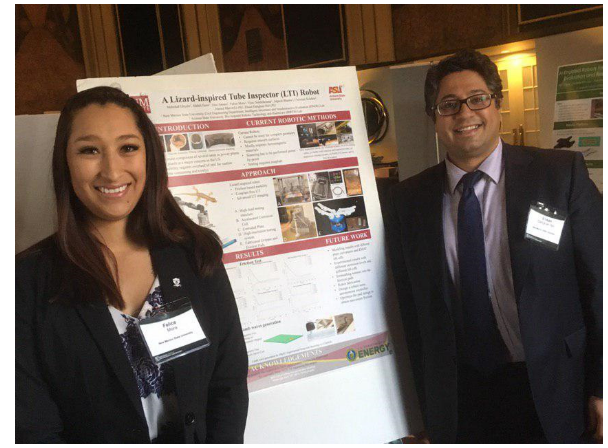
H. Marvi, E. Dehghan-Niri, and M. Ilami, "*Systems and methods for a Lizard-Inspired Tube Inspector (LTI) robot*", US patent pending, 2019.

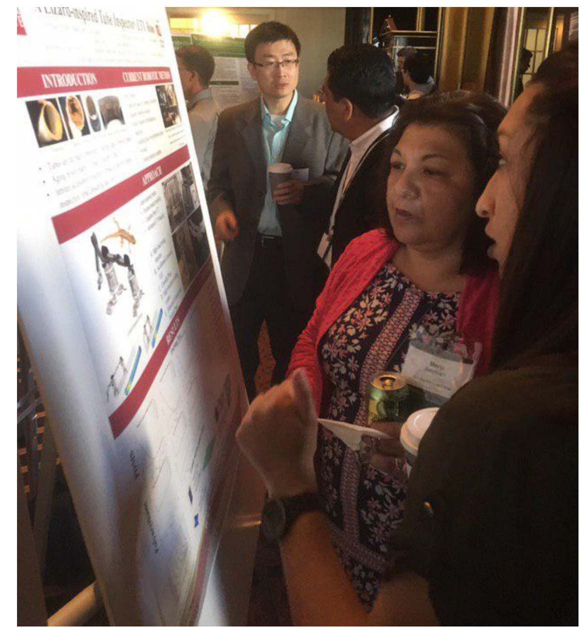
## Conferences

1. Ghyabi and E. Dehghan-Niri, "*Structural health monitoring of metallic plate-like structures for partial crack detection*", ASNT 28th Research Symposium, Hyatt Regency Orange County Garden Grove, CA, April 1-4, 2019.
2. Ghyabi and E. Dehghan-Niri, "Comparison of Coverage Areas of Two Different Sensor Network Arrangements for Structural Health Monitoring of Plate-Like Structures", SPIE Smart Structures + Nondestructive Evaluation, Denver, CO, 3-7 March, 2019.
3. S. Zamen, M. Ilami, V. Senthilkumar, H. Marvi, and E. Dehghan-Niri, "Experimental Evaluation of Friction Effects on Lamb Waves Generation", ASNT Annual Conference, Virtual, Nov. 2020.
4. H. Nemati, M. Ilami, J. Bhadra, H. Marvi, and E. Dehghan-Niri, "Evaluation of curvature effects on the performance of an integrated robotic gripper equipped with electromagnetic acoustic transducers", ASNT Annual Conference, Virtual, Nov. 2020.
5. H. Nemati, F. Alvidrez, A. Das, N. Masurkar, M. Rudraboina, H. Marvi and E. Dehghan-Niri, "Toward Automated Ultrasonic Inspection of Pipelines and Tubular Components" ASNT Research Symposium, Virtual, March 2021

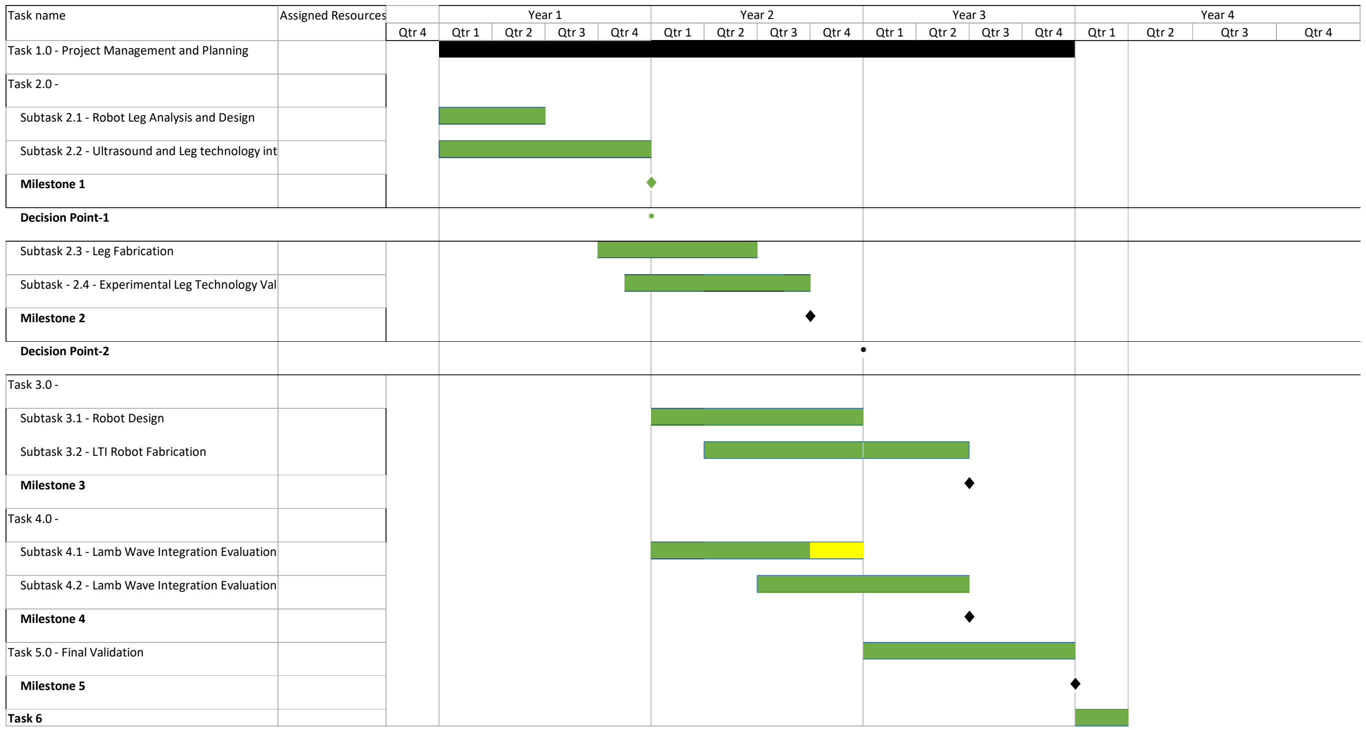
# FE's future workforce



# Challenges, current status and next steps





**Next steps: 1. optimize the LTI robot and 2. develop DL algorithms for robotic inspection**

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# Q&A

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# Concluding Remarks

Review how results apply directly to strategic goals

**U.S. Department of Energy Office of Fossil Energy 2018–2022**

# STRATEGIC VISION

**FE Strategic Goal 1.** Develop secure and affordable fossil energy technologies to realize the full value of domestic energy resources.

| Objectives | Sub-Objectives |
|---|---|
| 1.4 – Create smart infrastructure technologies for fossil energy | 1.4.1 – Develop advanced, integrated tools for transmission, delivery, and underground storage systems<br>1.4.2 – Develop technologies to reduce losses of natural gas in transmission and distribution infrastructure<br>1.4.3 – Create new multi-purpose pipeline technology that will enable the reliable transport of hydrocarbons, hydrogen, $CO_2$, and other high-value materials |

**FE Strategic Goal 2.** Enhance U.S. economic and energy security through prudent policy, advanced technology, and the use of strategic reserves.

| Objectives | Sub-Objectives |
|---|---|
| 2.1 – Protect the U.S. economy from severe petroleum supply interruptions | 2.1.1 – Maintain operational readiness to release petroleum products from the Strategic Petroleum Reserve (SPR), the Northeast Gasoline Supply Reserve, and the Northeast Home Heating Oil Reserve<br>2.1.2 – Conduct legislatively directed sales from the SPR efficiently and effectively<br>2.1.3 – Share technical expertise, best practices, and lessons learned from SPR operations with international partners in support of global petroleum stockpiling<br>2.1.4 – Carry out the SPR Life Extension Phase II Project<br>2.1.5 – Make efficient use of excess storage capacity resulting from legislatively directed oil sales |
| 2.2 – Advance technologies to improve the efficiency, reliability, emissions, and performance of existing fossil-based power generation | 2.2.1 – Improve the efficiency of existing coal-fired power plants<br>2.2.2 – Improve the reliability, emissions, and performance of existing coal-fired power plants |

**FE Strategic Goal 4.** Develop and maintain world-class organizational excellence.

| Objectives | Sub-Objectives |
|---|---|
| 4.1 – Drive enterprise-wide culture of high performance, innovation, empowerment, and scientific integrity | 4.1.1 – Develop and implement performance-reporting processes and tools that enable effective organizational decision making<br>4.1.2 – Align human capital strategies and practices to the *FE 2018–2022 Strategic Vision*, ensuring employees are well positioned to succeed in delivering the mission<br>4.1.3 – Promote employee engagement and partnerships within the FE workforce that drive success<br>4.1.4 – Cultivate and maintain a highly qualified, diverse, and well-trained workforce capable of achieving the FE mission and objectives |
| 4.2 – Promote knowledge sharing and transparent communication | 4.2.1 – Develop and implement an Information Management Strategy defining the roadmap of goals, strategies, and objectives to implement technology-enabled business management and knowledge management systems<br>4.2.2 – Develop, execute, and monitor a strategic communications plan for internal and external stakeholder engagement |
| 4.3 – Foster responsible stewardship of resources, facilities, a safe work environment, and the communities FE serves | 4.3.1 – Strengthen values-based safety culture and maintain the highest standards of workplace safety, health, and security for all employees, facilities, and information<br>4.3.2 – Maintain environmental stewardship<br>4.3.3 – Align financial and infrastructure resources to the *FE 2018–2022 Strategic Vision* |

# Strategic alignment of project to Fossil Energy (FE) objectives

The current project is inline with three of the strategic goals identified by Assistant Secretary for Fossil Energy

**Current Status of project:**

Currently the LTI robot is in **TRL 3-4 level**

| | |
|---|---|
| TRL 4 | Has laboratory-scale testing of similar equipment systems been completed in a simulated environment? |
| TRL 3 | Has equipment and process analysis and proof of concept been demonstrated in a simulated environment? |

**Industry/input or validation:**

The PI is regularly seeking feedbacks from scientist and engineers in **GE power**. The final LTI robot will be demonstrated at the end of the project to robotic and NDT section at GE Power.

## 2018–2022 STRATEGIC GOALS

**FE's four Strategic Goals are:**

**1. Develop secure and affordable fossil energy technologies to realize the full value of domestic energy resources.**

**2. Enhance U.S. economic and energy security through prudent policy, advanced technology, and the use of strategic reserves.**

3. Promote exports of domestically produced hydrocarbons and fossil energy technologies.

**4. Develop and maintain world-class organizational excellence.**

# Materials Evaluation special issue

## Robotic Inspection special issue

Materials Evaluation, Technical Focus Issue on Robotic Inspection, to be published in **July 2021**.

H. Nematia, F. Alvidrez, A. Das, N. Masurkar, M. Rudraboina, **H. Marvi**, and **E. Dehghan-Niri**, "Integrating electromagnetic acoustic transducers in a modular robotic gripper for inspecting tubular components" Materials Evaluation, July 2021, In press

C. Lara, J. Villamil, A. Abrahao, A. Aravelli, G. Daldegan, S. Sarker, D. Martinez, **D. McDaniel**, "Development of an Innovative Inspection Tool for Superheater Tubes in Fossil Energy Power Plants" Materials Evaluation, July 2021, In press

X. Shi1, A. Olvera, C. Hamilton, J. Li, L. Utke, **A. Petruska**, Z. Yu, **Y. Deng** and **H. Zhang**, "AI-enabled Robotic NDE for Structural Damage Assessment and Repair" under review

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