The Lizard-inspired Tube Inspector (LTI) Robot

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Project Description and Objectives

Problem statement

Thinning

Deposit corrosion

Pitting corrosion

Stress corrosion cracking

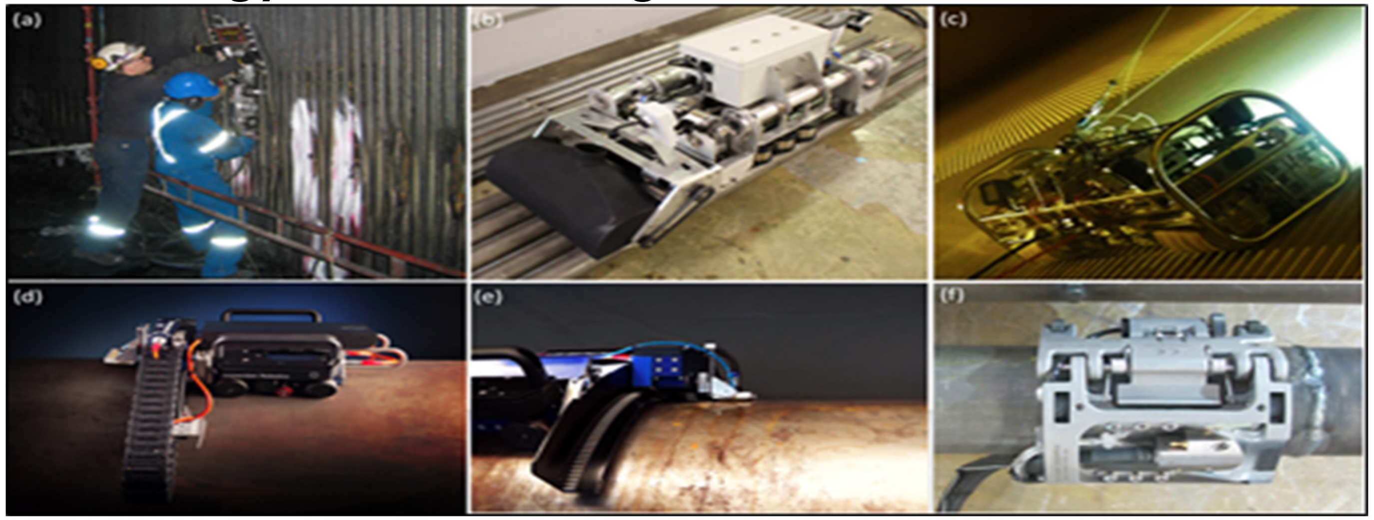
- Tubes and pipelines are the main component of several units in power plants and oil, gas and water transmission.
- Aging power plants and pipelines is a major concern in the US.
- regular inspection is time consuming and costly (e.g. limited accessibility in power plants' units requires overhaul of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

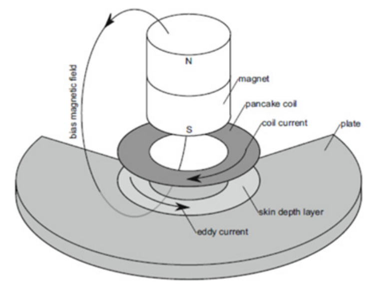
Project Description and Objectives

What do we propose?

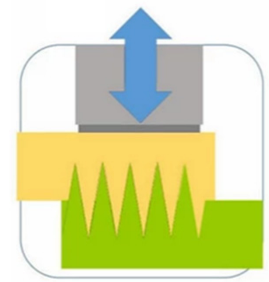
- **Objective 1:** to integrate automation with couplant-free ultrasound transmission technology and develop an advanced Lamb wave based imaging algorithm to detect and evaluate crack and corrosion defects in tubes/pipes using a network of couplant-free ultrasound sensors placed at the location of the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

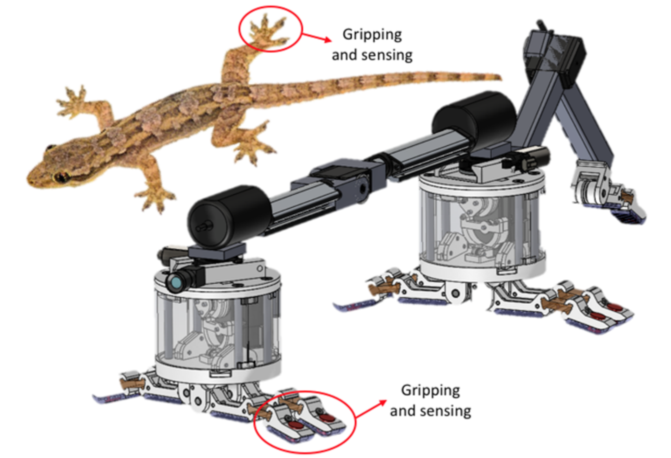


EMAT

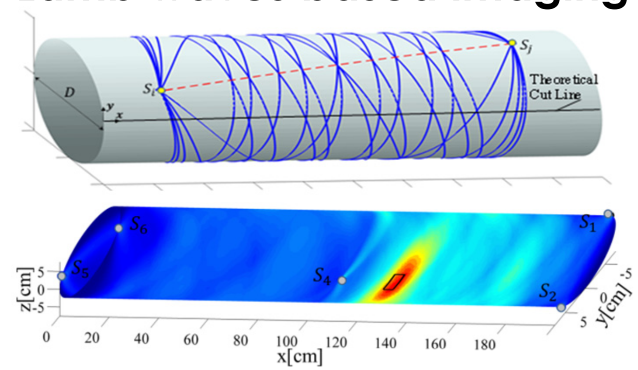


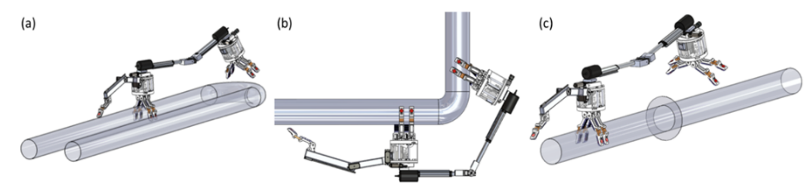
Friction-based ultrasound

Objective 2
Friction-based mobility

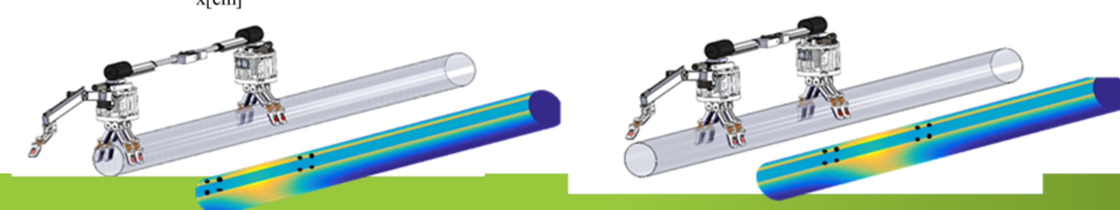


Lamb waves based imaging





Final Goal



Strategic alignment of project to Fossil Energy (FE) objectives

NATIONAL ENERGY TECHNOLOGY LABORATORY

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.

Assistant Secretary for Fossil Energy

Steven Winberg

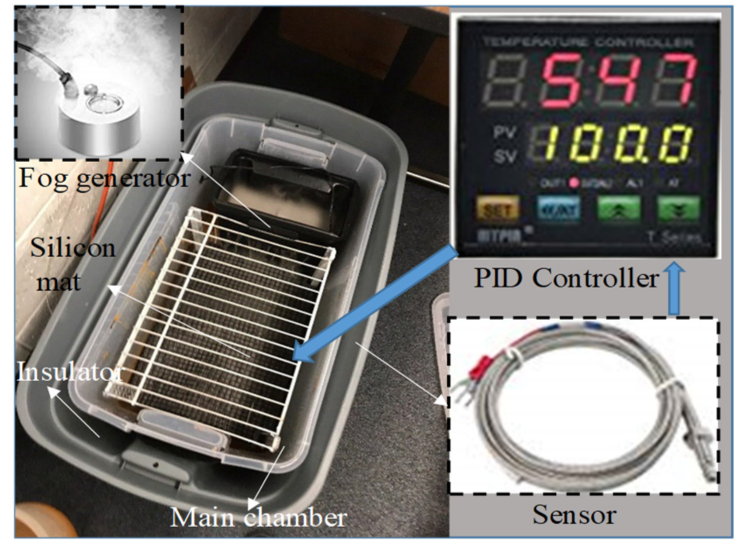
"This goal promotes U.S. domestic homegrown energy development to achieve energy security and jobs in energy and technology around the world. It also means producing fossil energy resources—oil, gas, and coal—**safely** and hand-in-hand with responsible environmental stewardship."

Couplant-free ultrasound generation

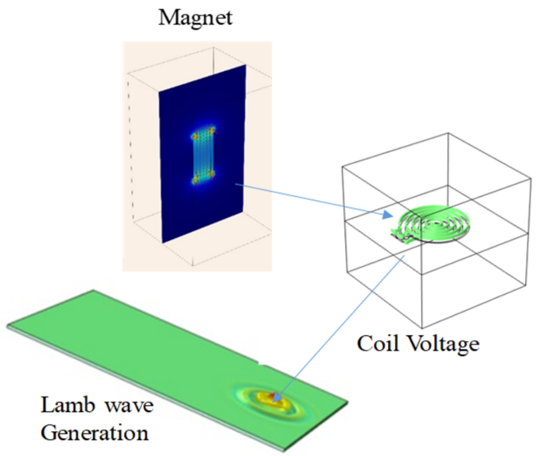
Electromagnetic acoustic transducer (EMAT)

Material	Elastic Modulus (GPa)	Poisso 's Ratio	Density (kg/m³)	Thicknes s (mm)
Stainless Steel - 316LASTM	200	0.25	8000	3.048

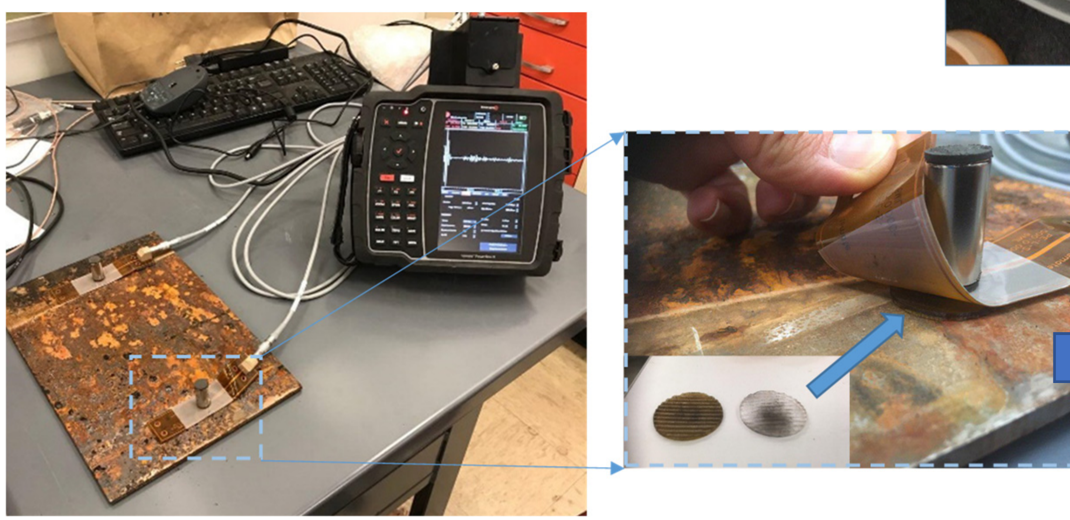
Corrosion Cell



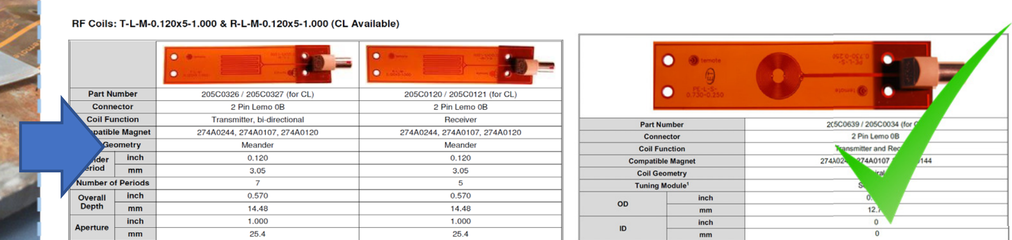
Numerical Simulation



Experimental validation



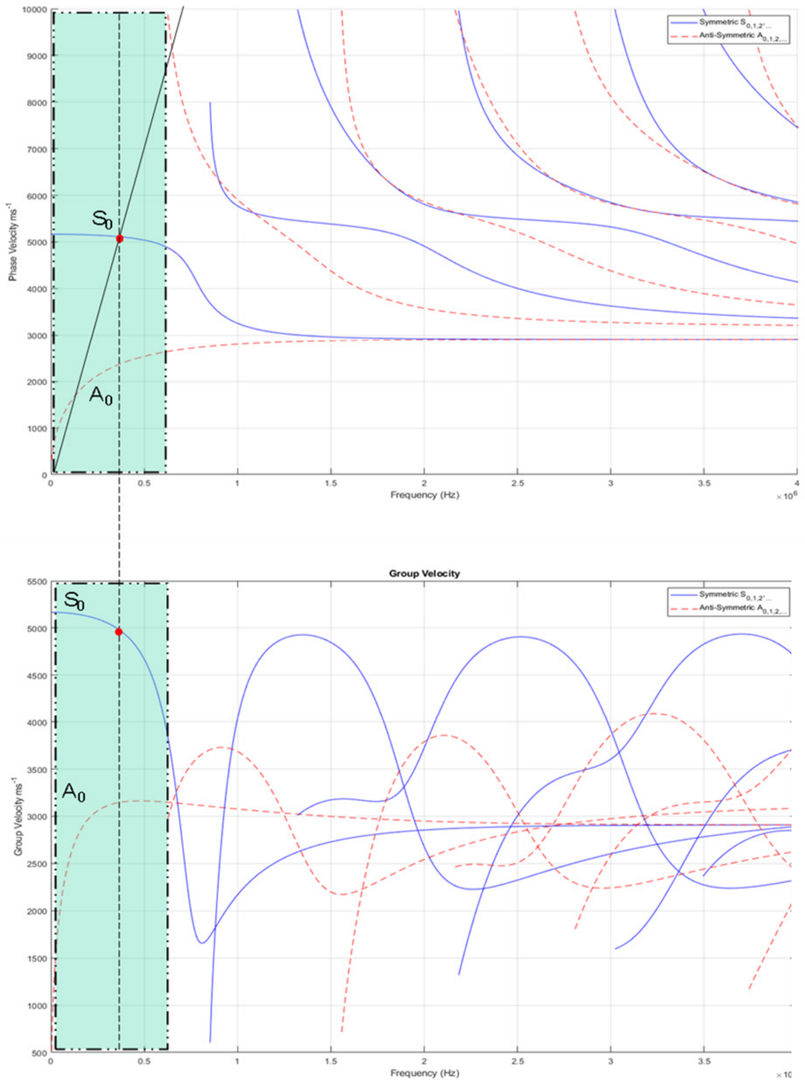
The coil was initially designed

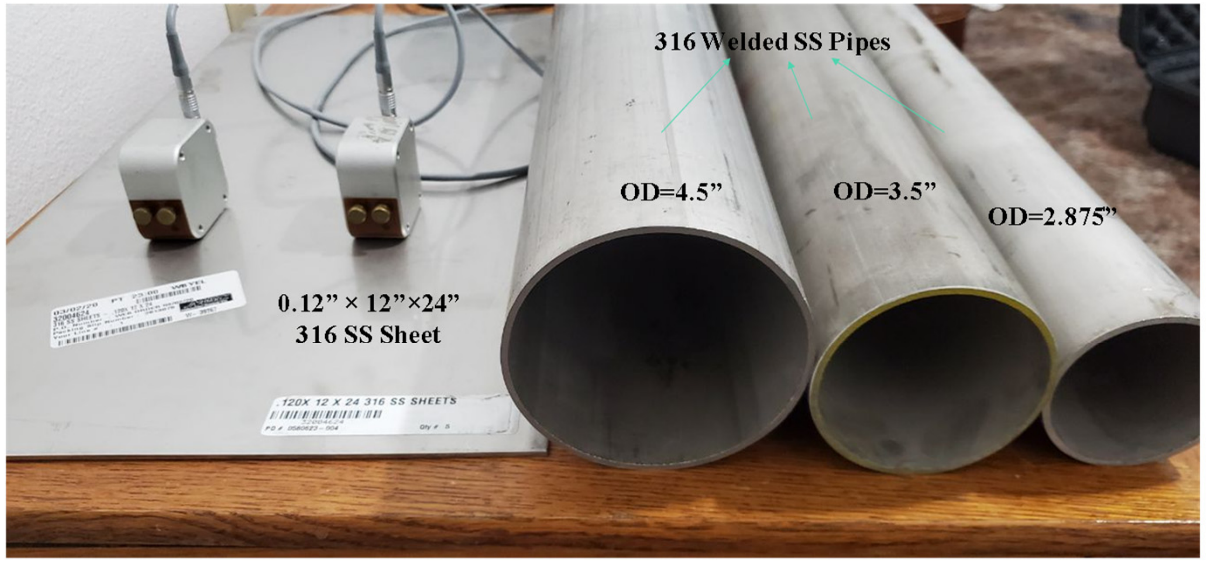


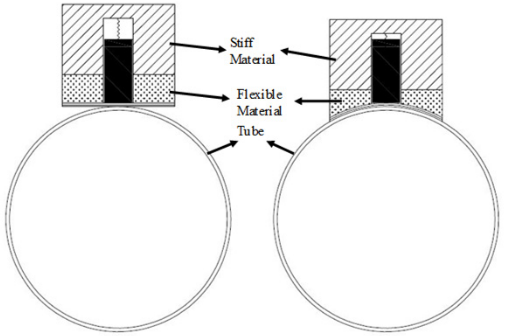
Minder coil for small diameter and spiral for large diameter

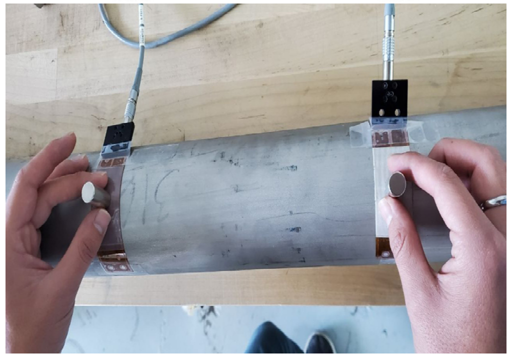
Couplant-free ultrasound generation

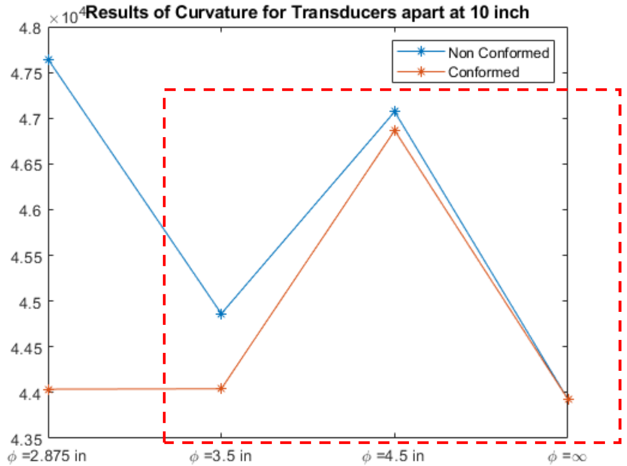
Electromagnetic acoustic transducer (EMAT) Lamb wave

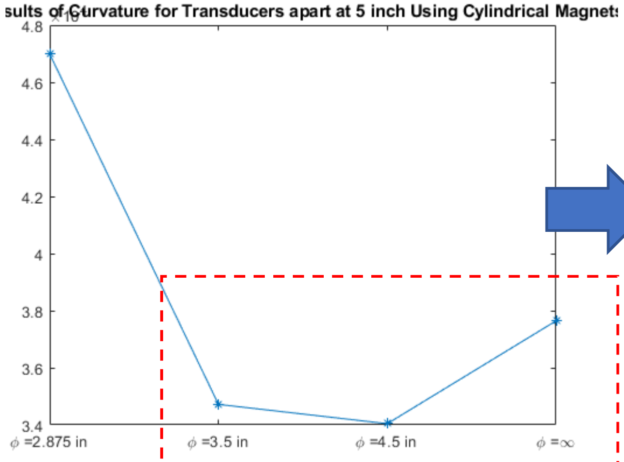








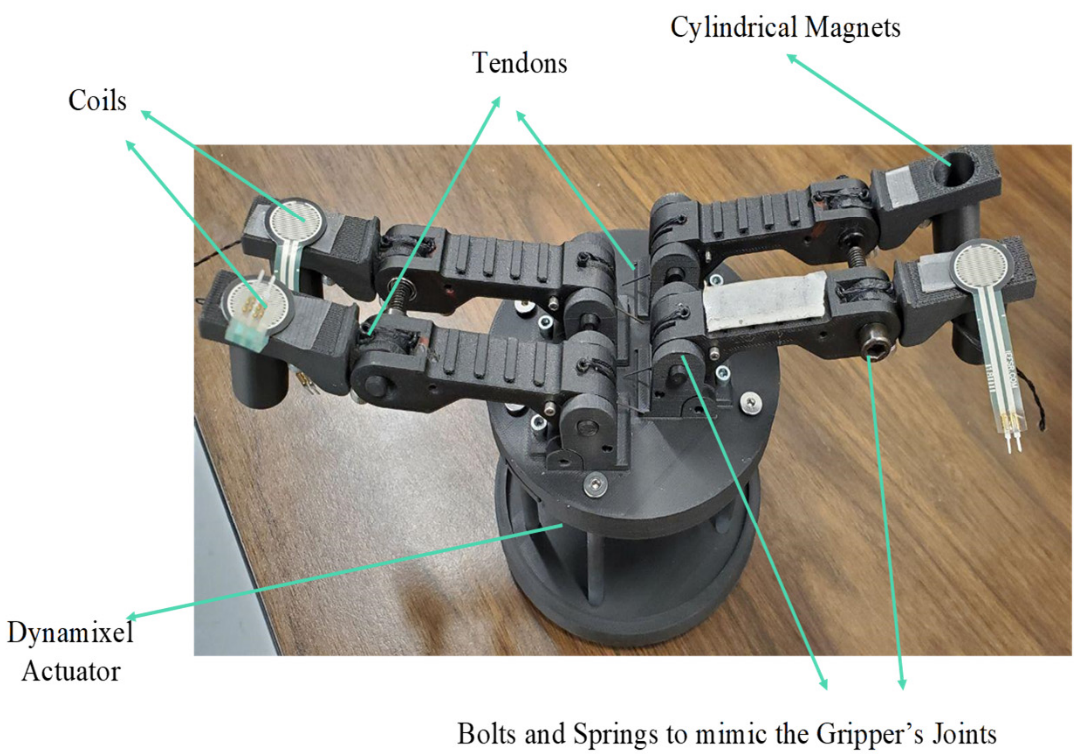


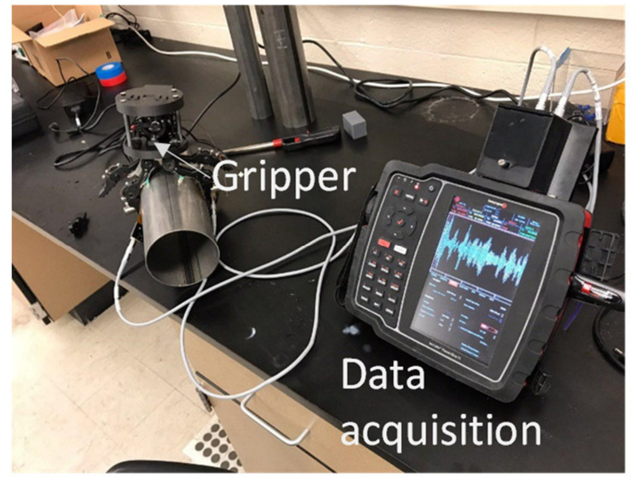


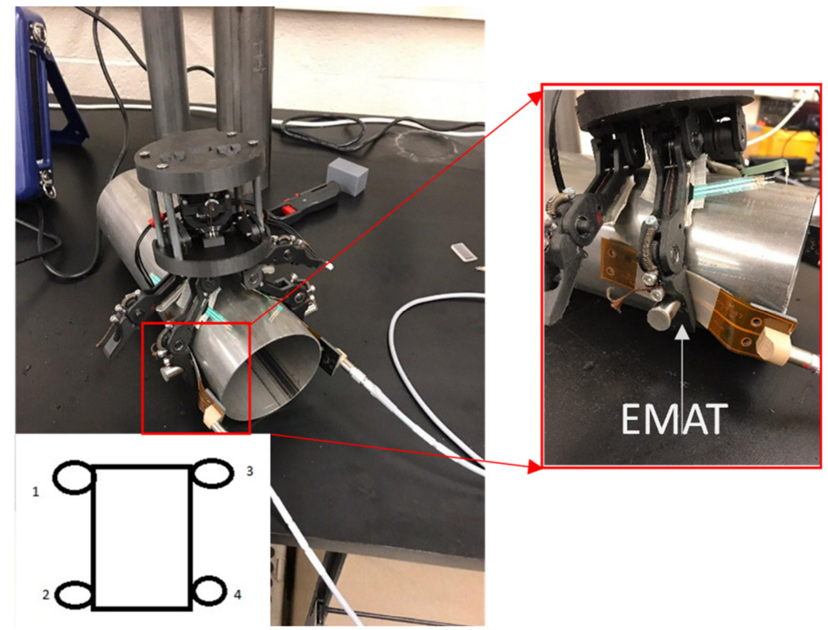
For dimeter larger than 3" the effect of curvature is negligible

Couplant-free ultrasound generation

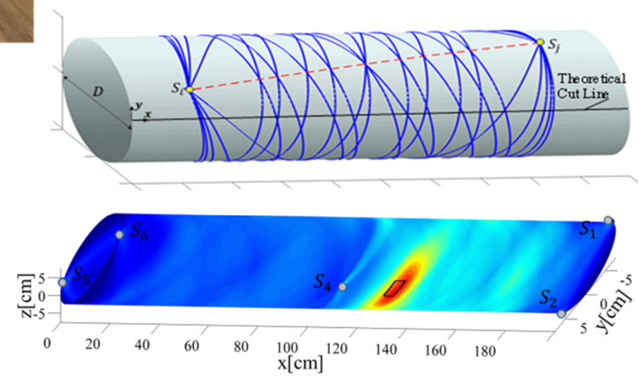
EMAT and gripper integration (gripper ver. 1)

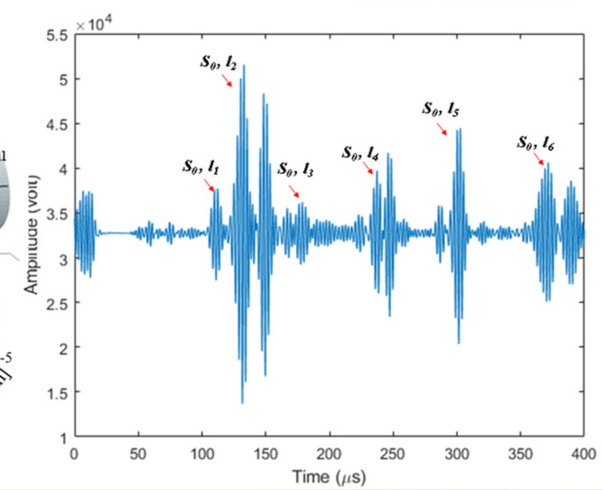






MHUI



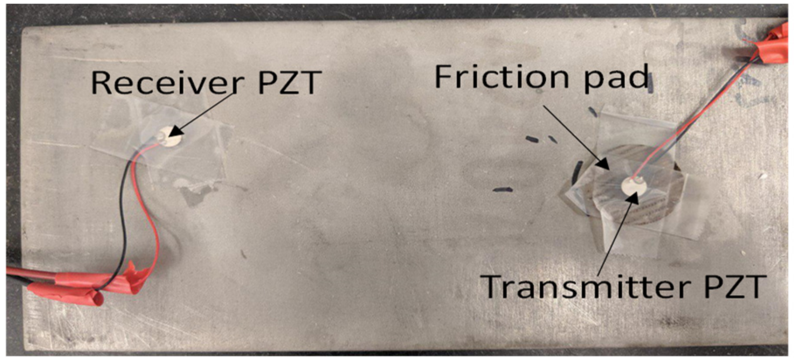


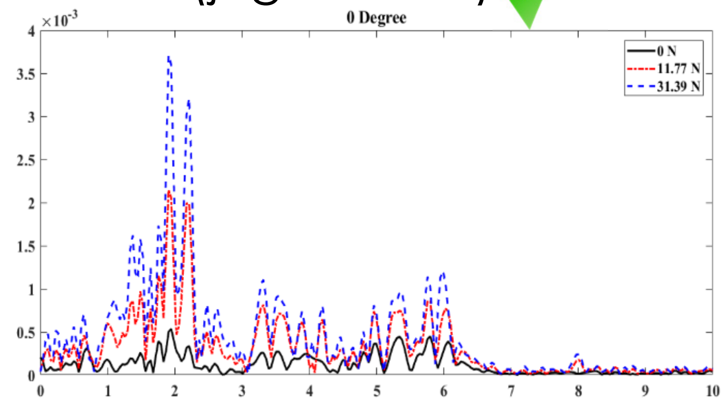
MHUI can be done with the current configuration of LTI sensing

Couplant-free ultrasound generation

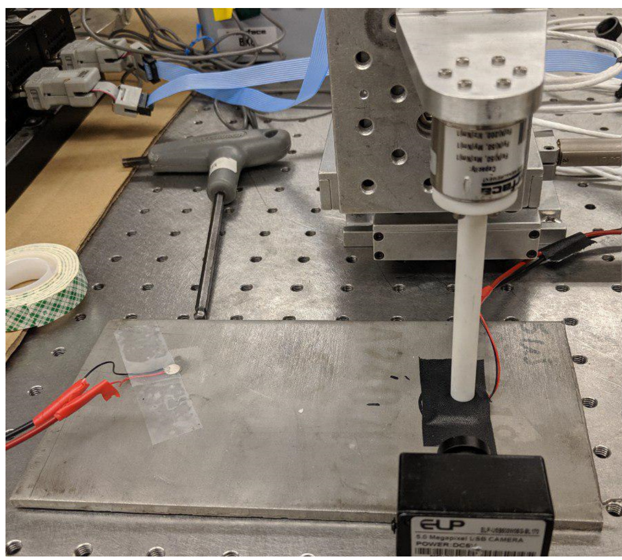
Friction based Lamb waves

Go-No-Go (jugular test)

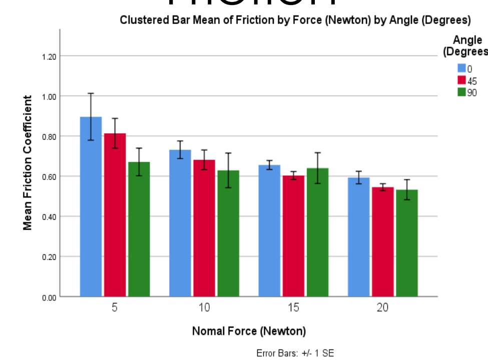




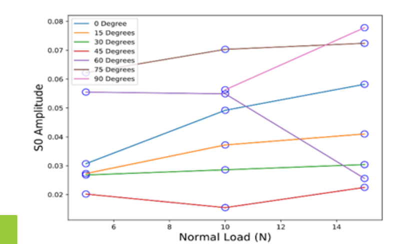
Low-load testing structure



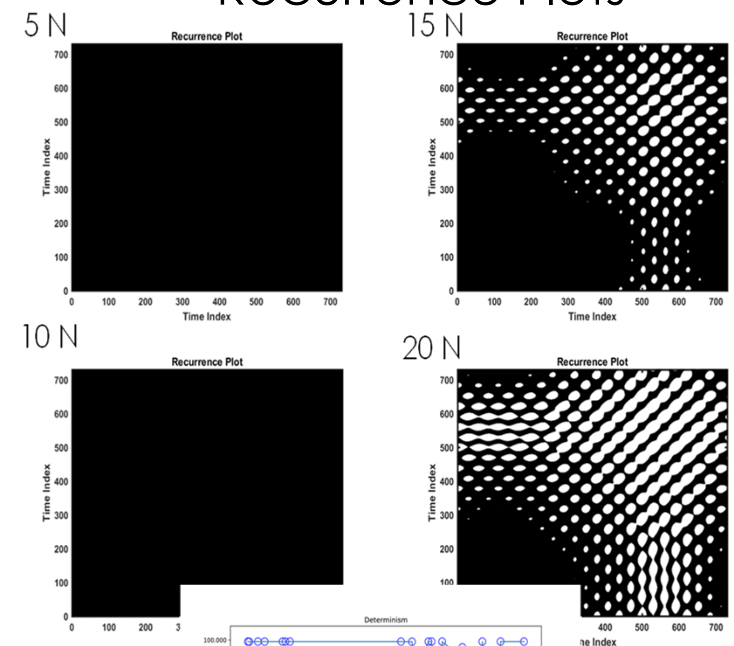
Friction

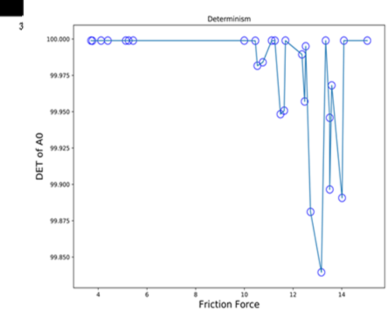


Lamb waves excitation



Recurrence Plots

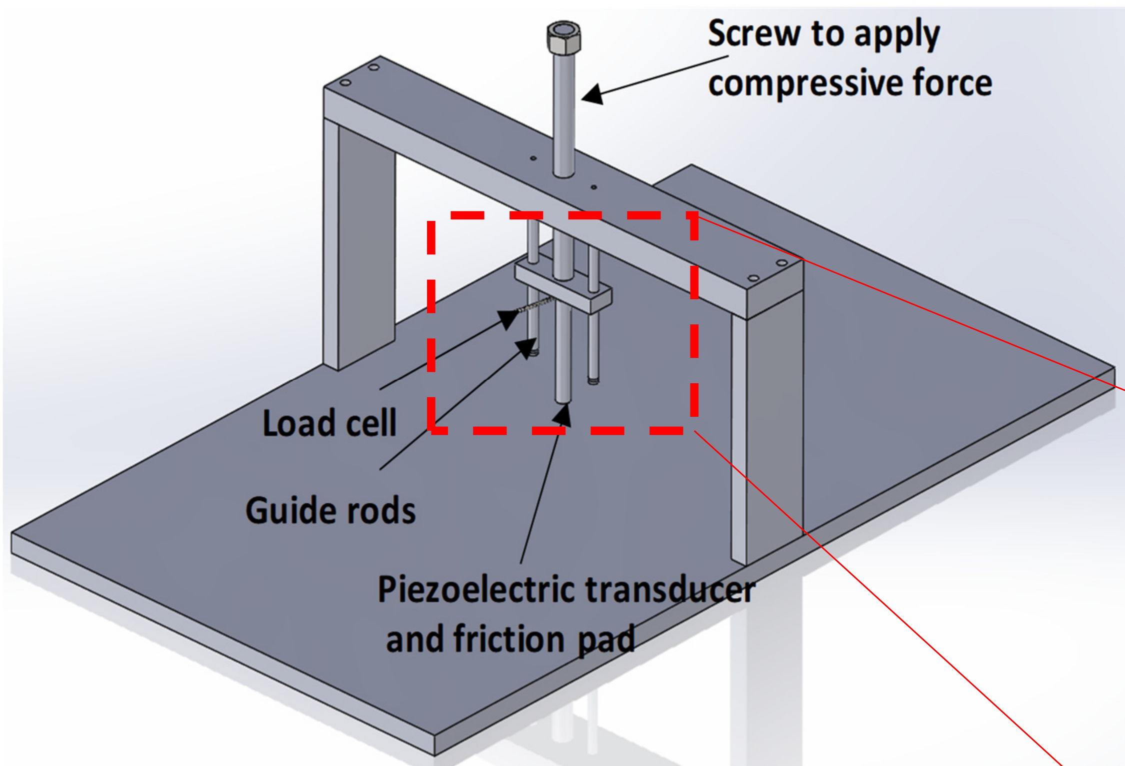


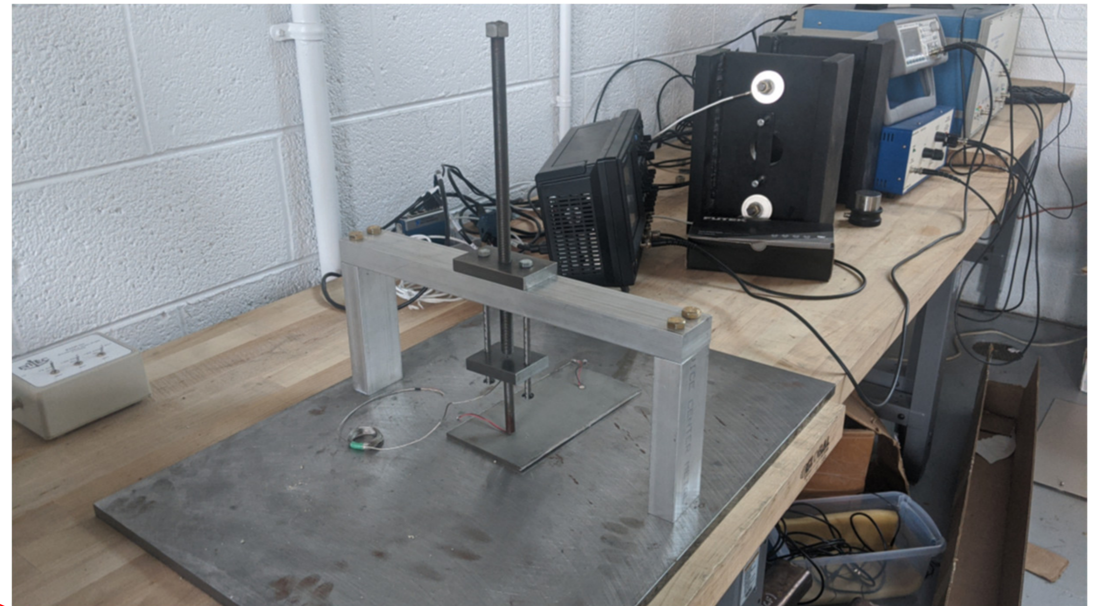


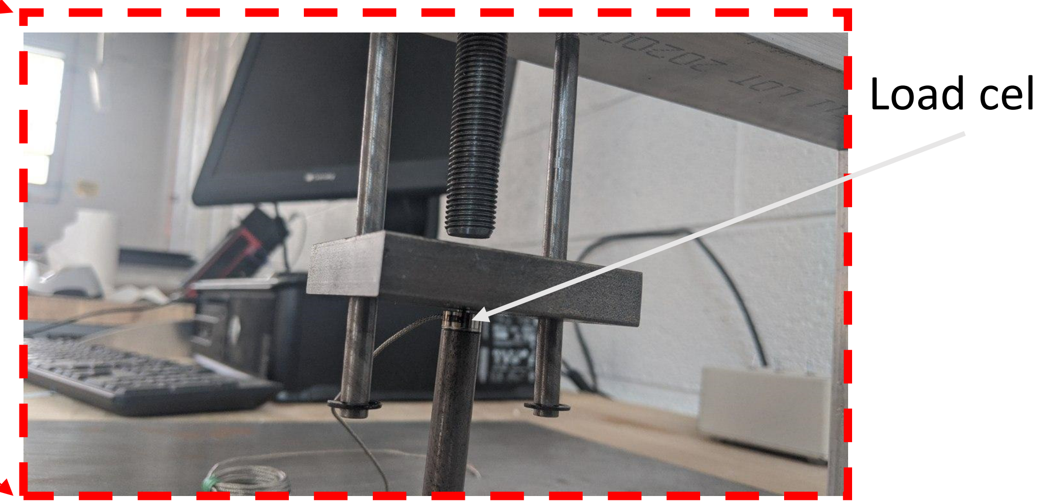
Chaotic behavior observed due to significant nonlinearity caused by friction

Couplant-free ultrasound generation

Friction based Lamb waves next step

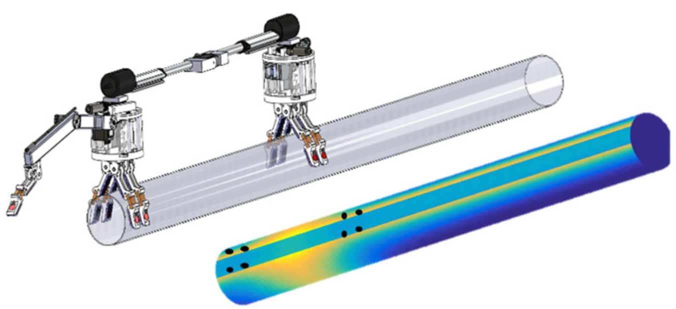


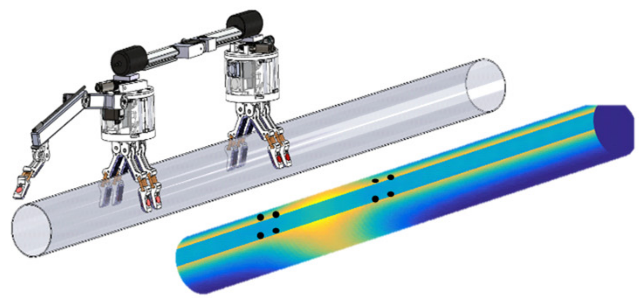


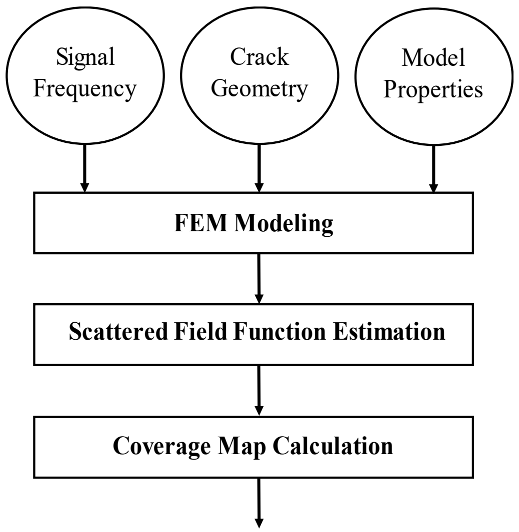


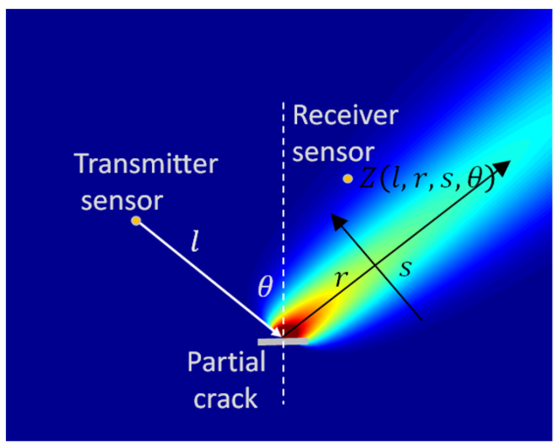
Lamb waves based imaging

Crack detection

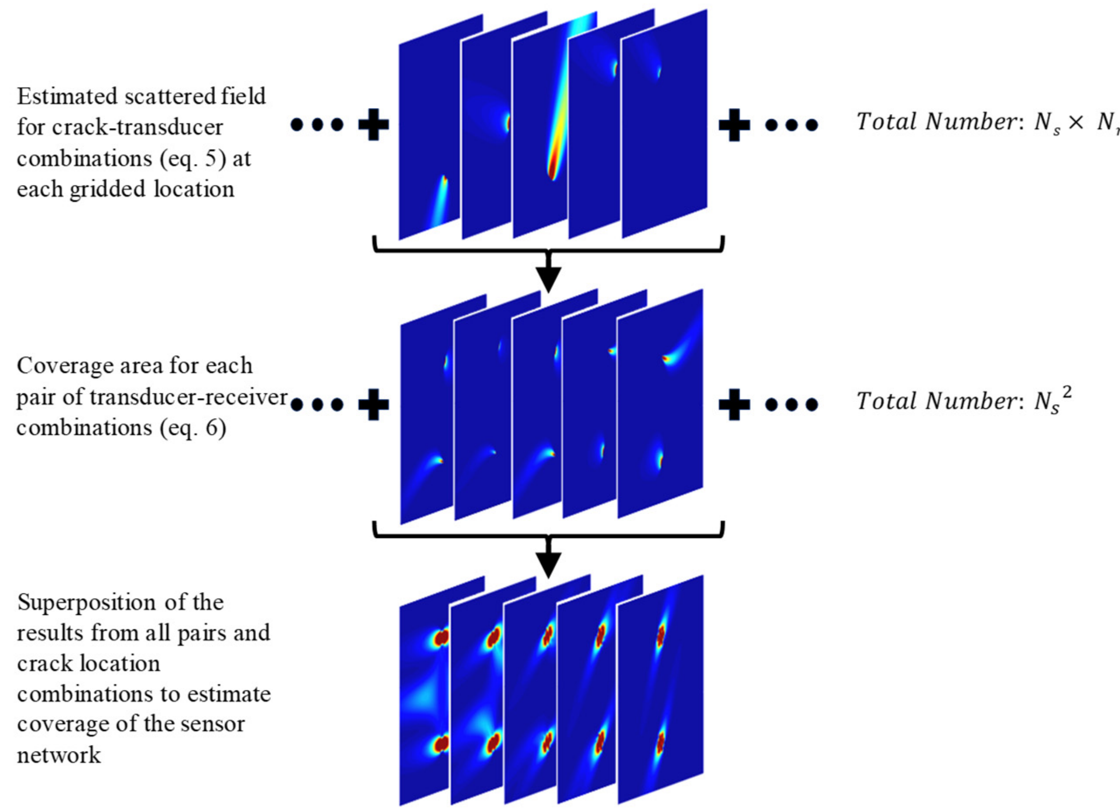








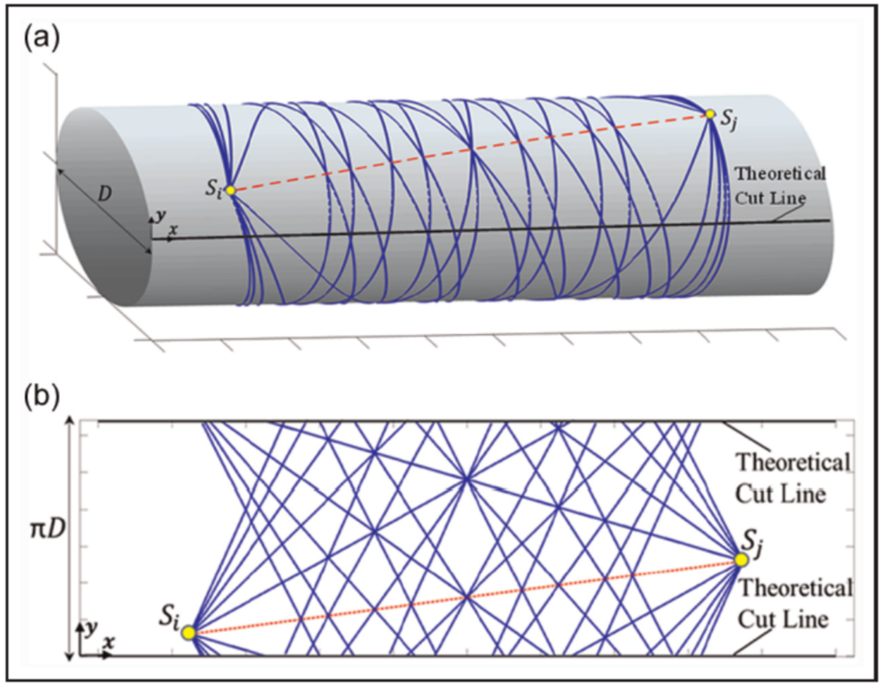
$$C_{\alpha}^{t,r}(x, y) = Z_{\alpha}^{t,c|x,y}(x_r, y_r)$$

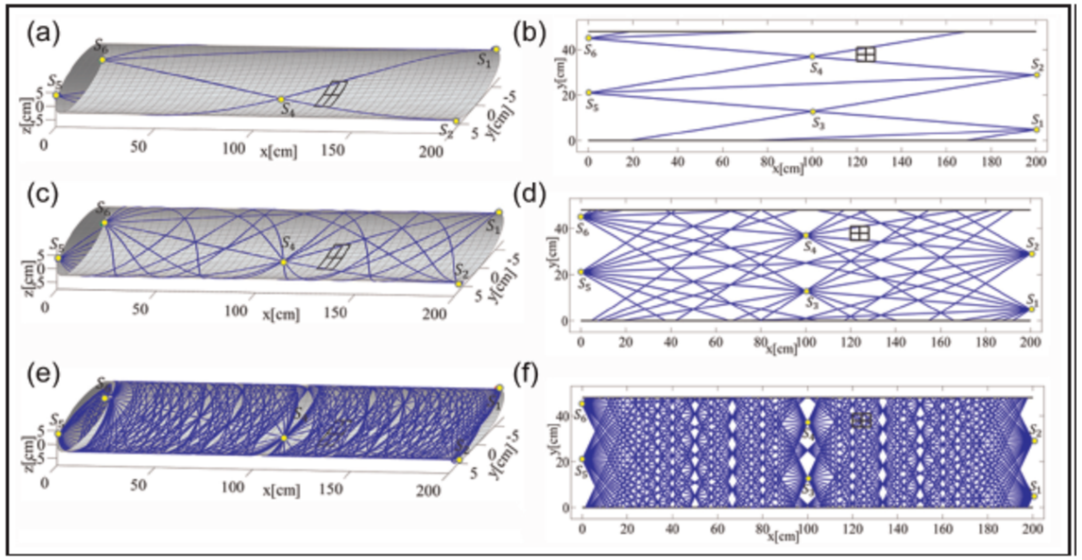


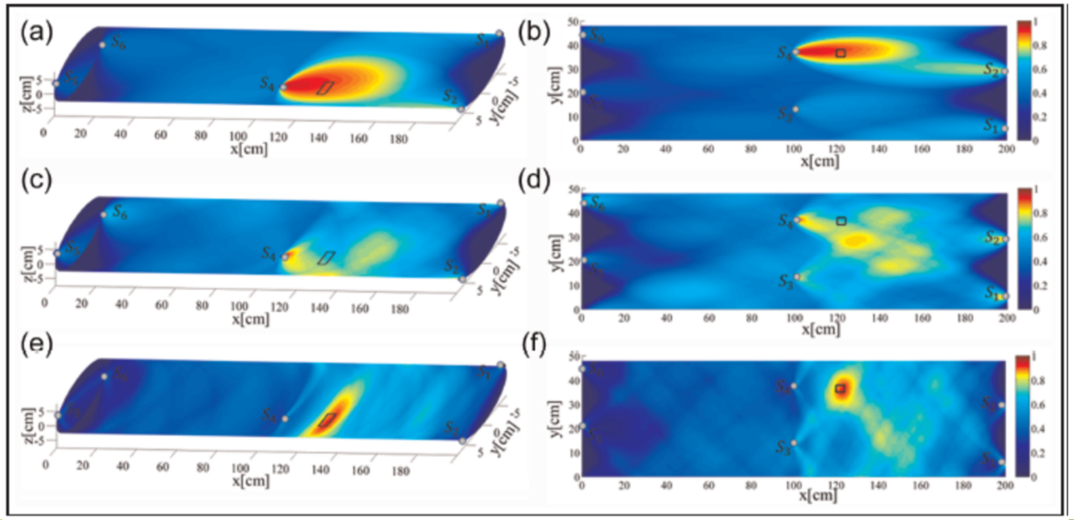
This numerical framework can predict the coverage area for detecting a critical crack based on LTI's location of grippers

Lamb waves based imaging

Corrosion detection multi-helical ultrasonic imaging MHUI





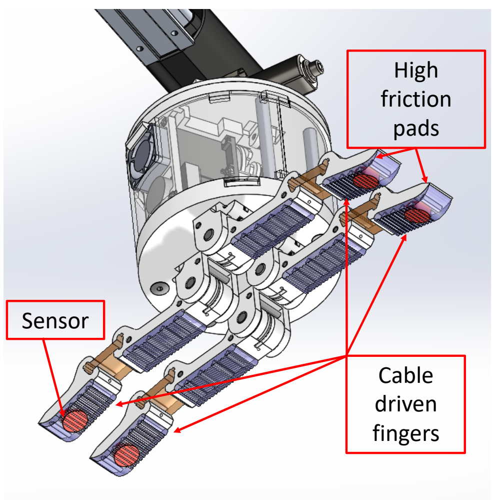


E. Dehghan-Niri, S. Salamone, "A Multi-helical ultrasonic imaging approach for the structural health monitoring of cylindrical structures", *Structural Health Monitoring: International Journal, vol. 14 no. 1, pp. 73-85, 2015.*

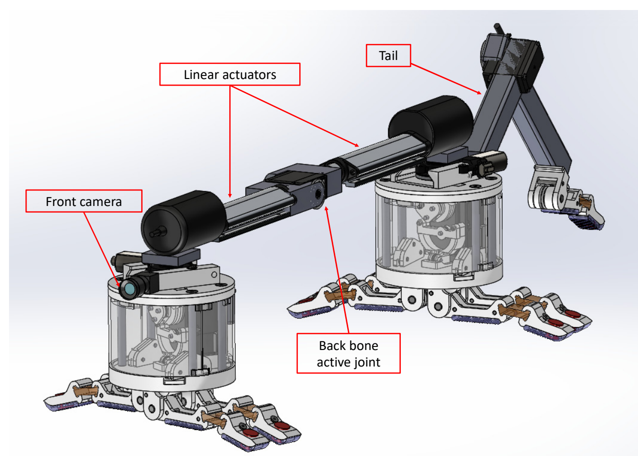
E. Dehghan-Niri, S. Salamone, "*Quantitative Corrosion Imaging of Pipelines using Multi-Helical Guided Ultrasonic Waves*", *Structural Monitoring and Maintenance, An international Journal, Vol. 3, No. 3, pp. 215-232, 2016.*

LTI Robot

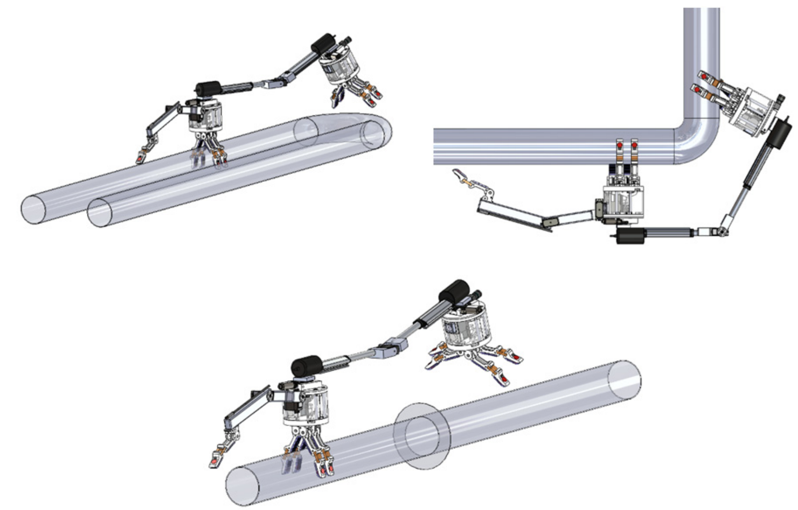
Multifunctional Gripper



Main Body

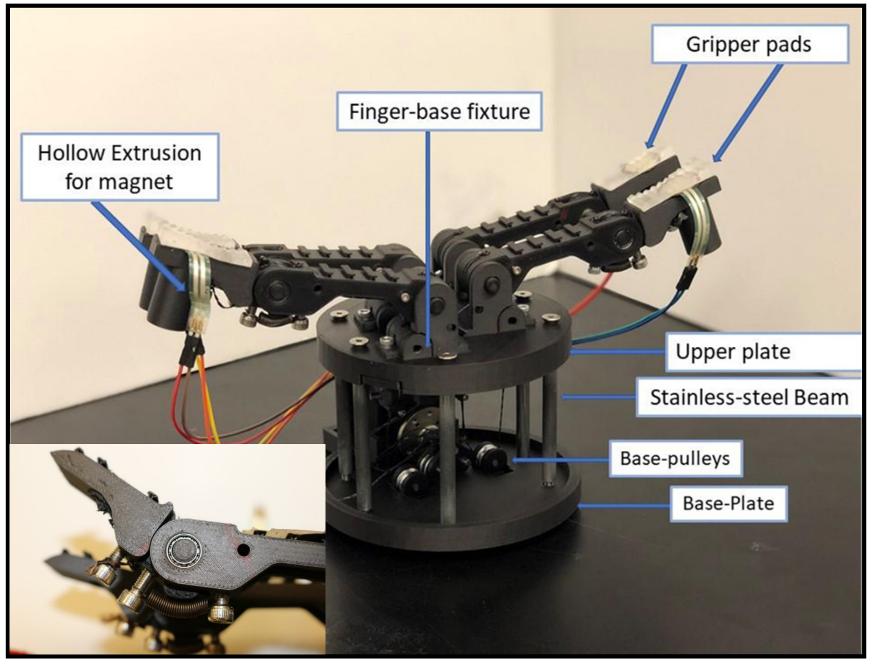


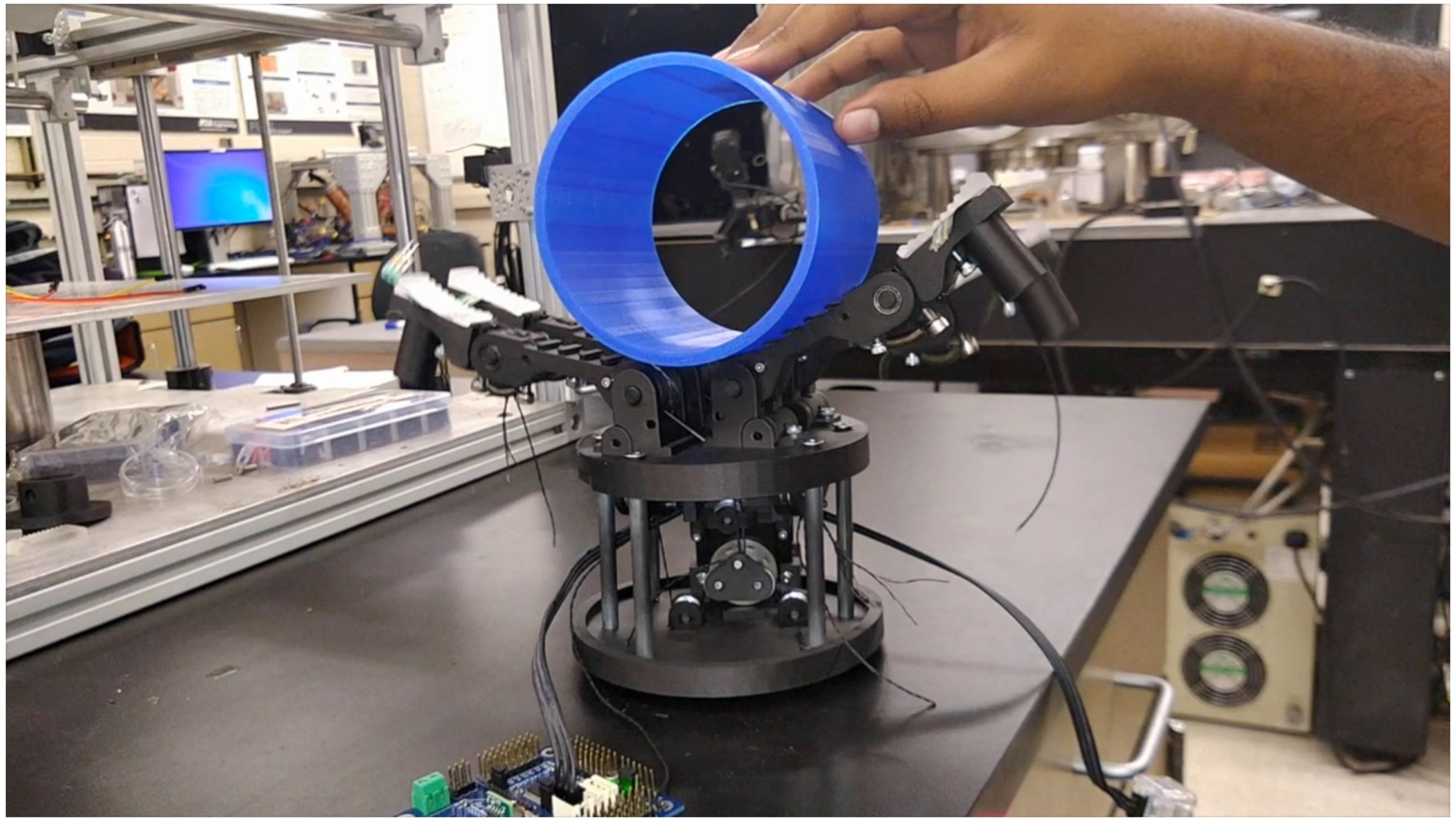
Experimentation



Multifunctional Gripper

Original Design (v1)

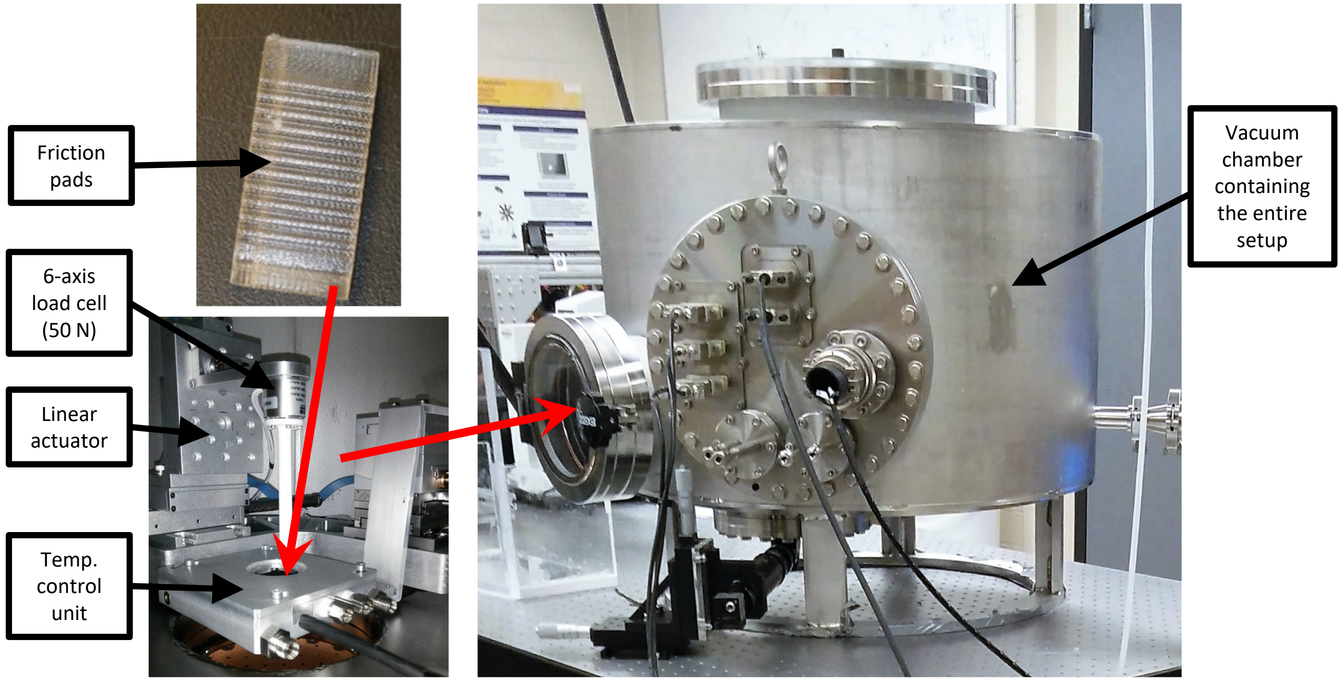




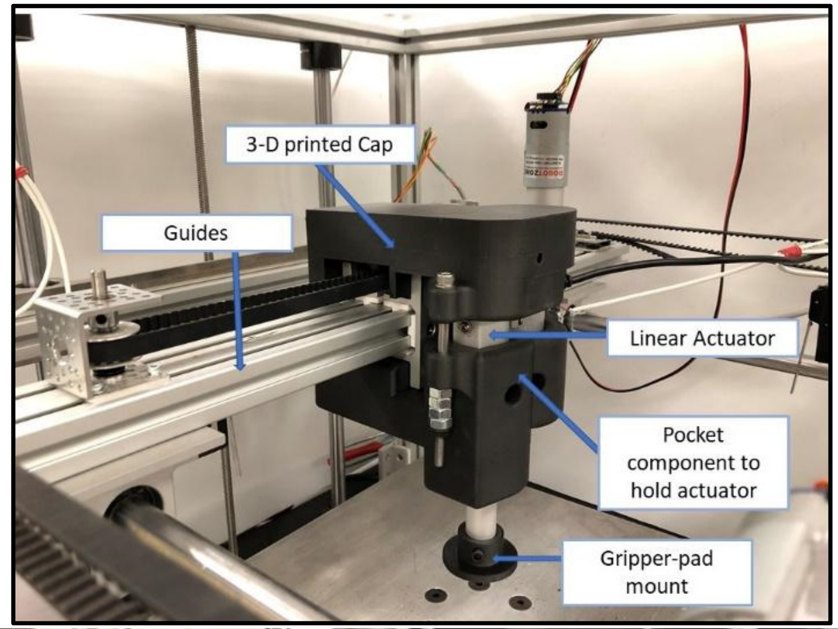
- This design was an upgrade to the Yale open-ended gripper design (Kevlar strings and pulleys).
- The kevlar strings tend to snap or lose their tension after multiple actuations of the gripper.
- The gripper can provide relatively small normal load

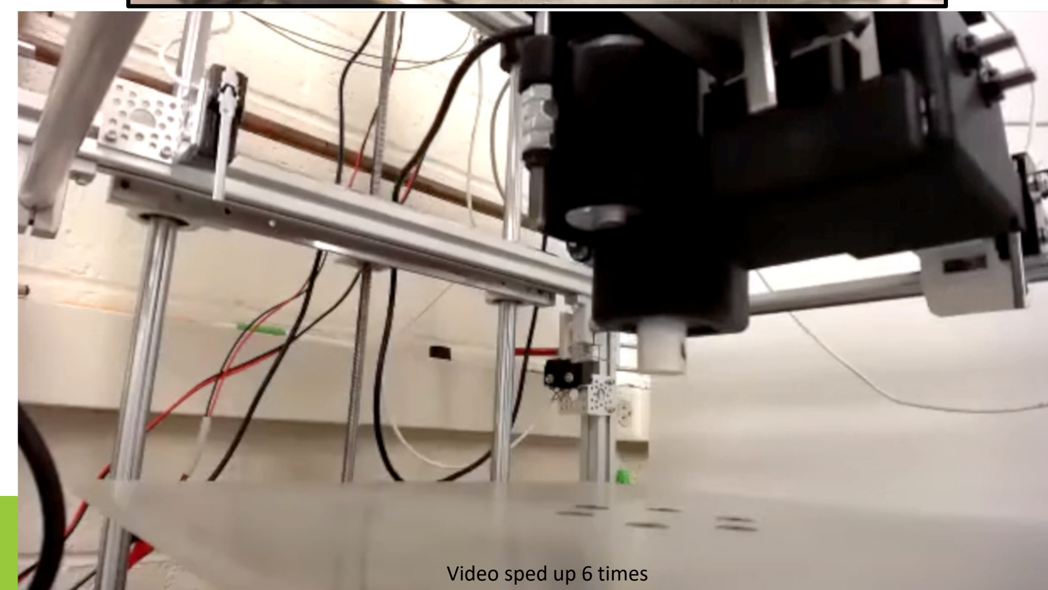
Friction characterization

Low Load



High Load

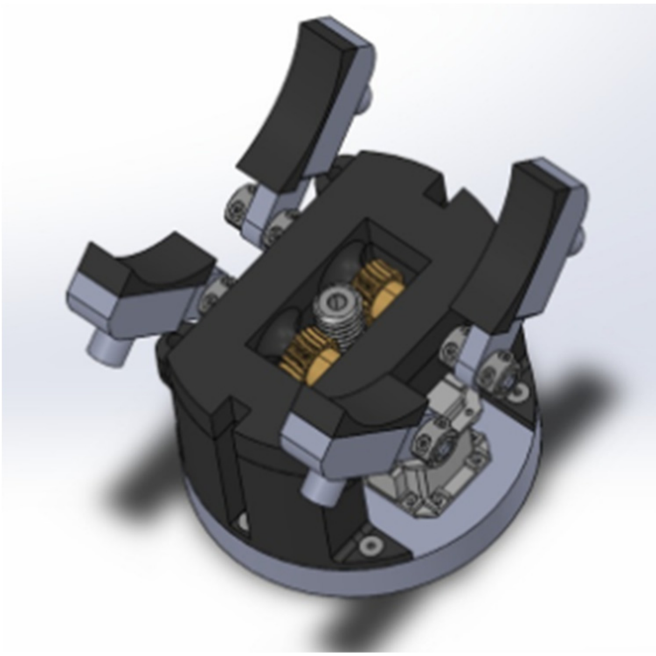


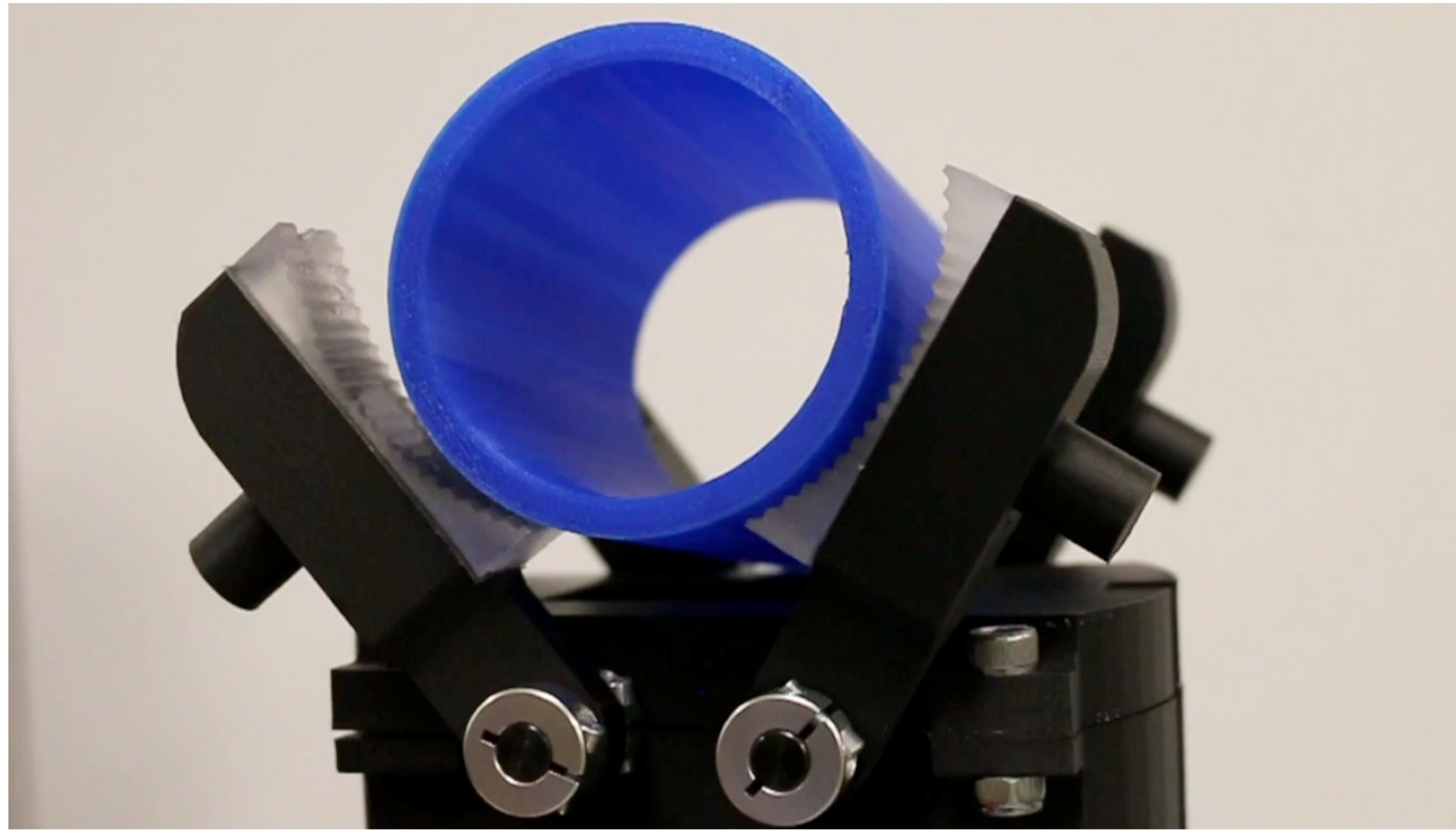


Material/ Test	Coefficient of Static Friction
PDMS 4.5mm/ Lateral	1.16±0.01
PDMS 4.5mm/ Longitudinal	0.96±0.02
PDMS 9.0mm/ Lateral	1.22±0.01
PDMS 9.0mm/ Longitudinal	0.86±0.01
Poly 4.5mm/ Lateral	0.33±0.00
Poly 4.5mm/ Longitudinal	0.39±0.01
Poly 9.0mm/ Lateral	0.49±0.01
Poly 9.0mm/ Longitudinal	0.33±0.00

Multifunctional Gripper

New Design (v2)



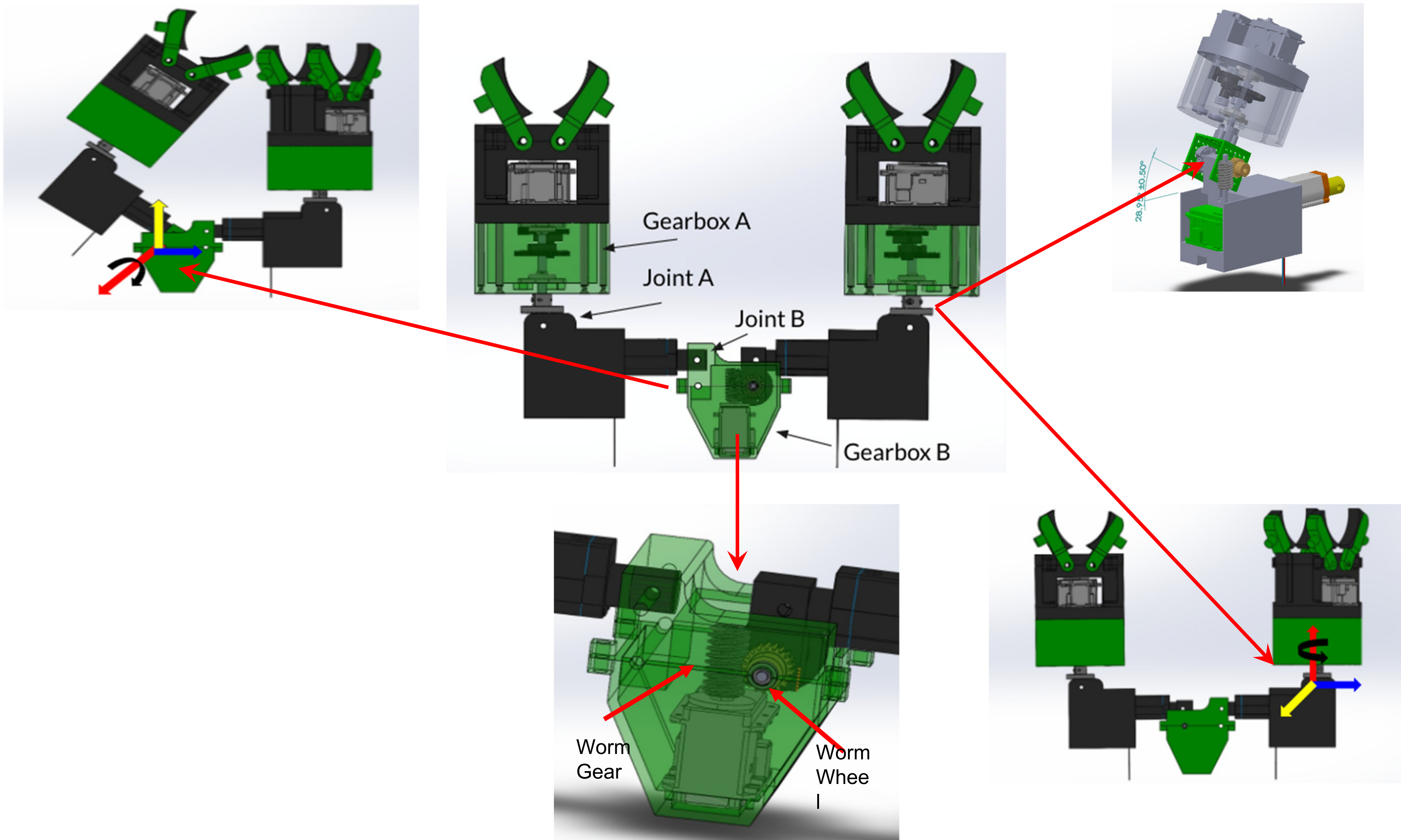


Video sped up 8 times

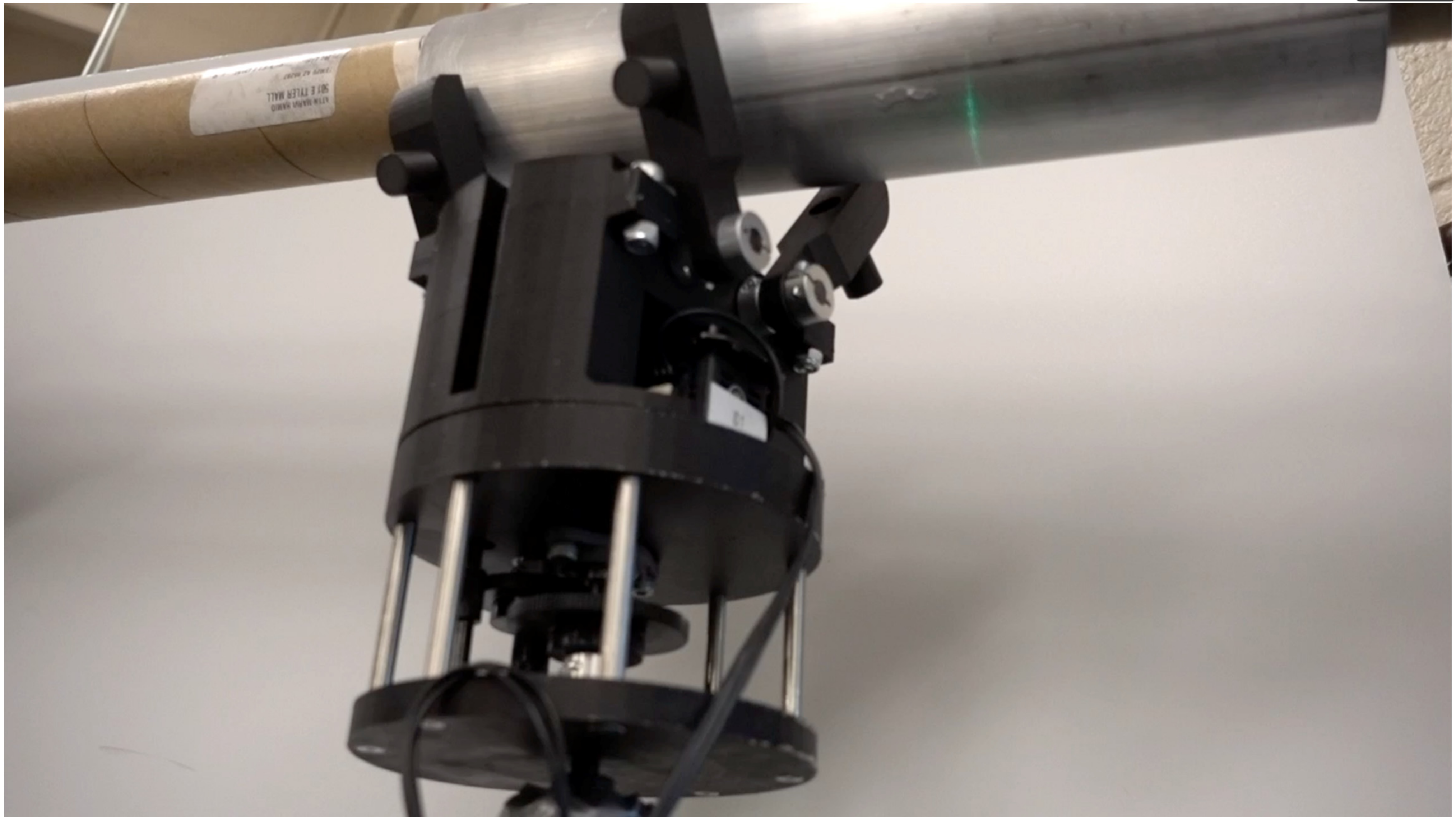
- The actuation mechanism of kevlar strings was replaced by a worm gear pair with a gear ratio of 1:10 to ensure a robust and stable actuation of the gripper.

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

Main body of the LTI robot



Half of the LTI robot in action



Video sped up 4 times

Outcomes, publications, patents

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. Hamidreza Nemati, Mahdi Ilami, Jalpesh Bhadra, Hamidreza Marvi and Ehsan Dehghan-Niri, *Evaluation of curvature effects on the performance of an integrated robotic gripper equipped with electromagnetic acoustic transducers*, 2020

3. Sina Zamen, Mahdi Ilami, Vijay Senthilkumar, Hamidreza Marvi, and Ehsan Dehghan-Niri1, *Experimental evaluation of friction effects on Lamb waves generation*, 2020

Journals

1. Mehrdad Ghyabi, Hamidreza Nemati and Ehsan 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, under review

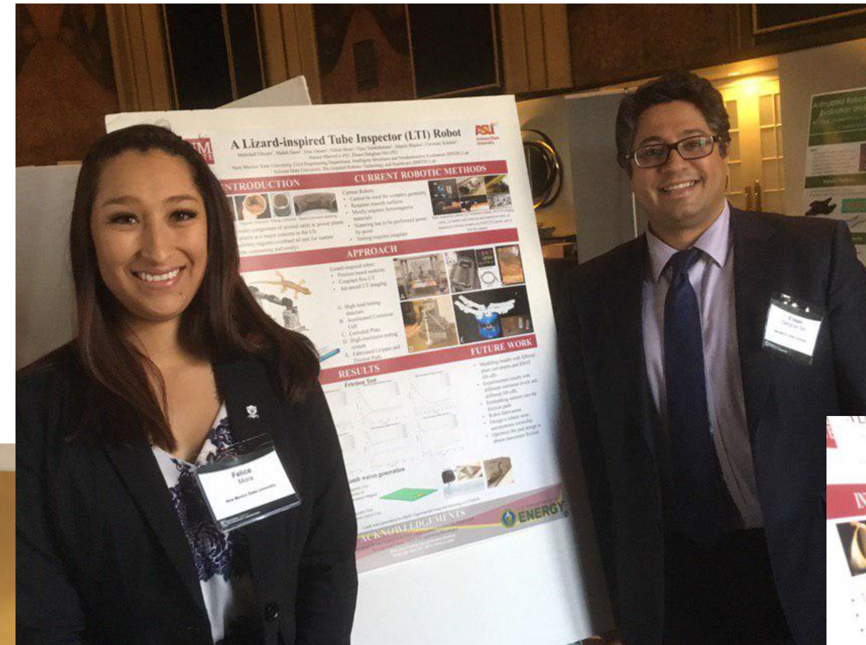
2. Sina Zamen, Ehsan Dehghan-Niri, Mahdi Ilami, Vijay Anand Senthilkumar, and Hamidreza Marvi, *Influence of clamping and friction force on the determinism characteristics of Lamb wave*, Applied Physics Letters, In preparation

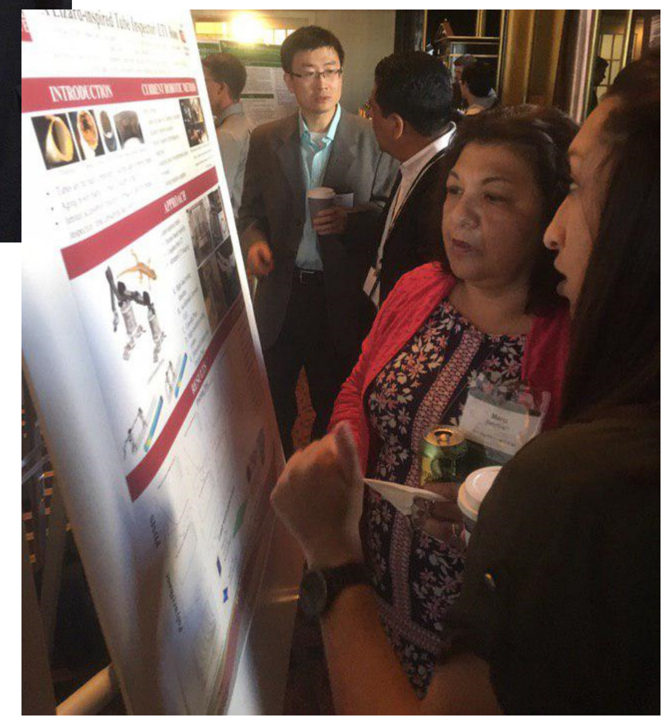
3. Ehsan Dehghan Niri and Hamidreza Marvi, *Bio-Inspired robotic Inspection*, Materials Evaluation, In preparation,(July 2021 special issue)

Patents

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

FE's future workforce





Concluding Remarks

NATIONAL ENERGY TECHNOLOGY LABORATORY

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 1.4.2 – Develop technologies to reduce losses of natural gas in transmission and distribution infrastructure 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 2.1.2 – Conduct legislatively directed sales from the SPR efficiently and effectively 2.1.3 – Share technical expertise, best practices, and lessons learned from SPR operations with international partners in support of global petroleum stockpiling 2.1.4 – Carry out the SPR Life Extension Phase II Project 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 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 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 4.1.3 – Promote employee engagement and partnerships within the FE workforce that drive success 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 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 4.3.2 – Maintain environmental stewardship 4.3.3 – Align financial and infrastructure resources to the *FE 2018–2022 Strategic Vision*

Concluding Remarks

Discuss which key challenges for fossil energy are addressed

According to Assistant Secretary for Fossil Energy **Mr. Steven Winberg** ""To that end, we will focus our R&D on five significant areas to address challenges currently confronting the industry: modernizing **the aging coal fleet**; revolutionizing energy systems to give power producers options in the future; engineering an evolving energy infrastructure; water management; and mastering the subsurface to engineer geologic systems."

Maintain operational readiness to release petroleum products from the Strategic Petroleum Reserve, the Northeast Gasoline Supply Reserve, and the Northeast Home Heating Oil Reserve

Operational readiness is a steady-state period during which each reserve site is configured and ready to draw down, upon direction of the President or the Secretary of Energy. Execution of a comprehensive maintenance program (specially aging pipelines).

Water Security Grand Challenges: Develop advanced, integrated tools for transmission, delivery, and underground storage systems "Create tools to assess and quantify infrastructure disruption, such as disruption from corrosion-related incidents"

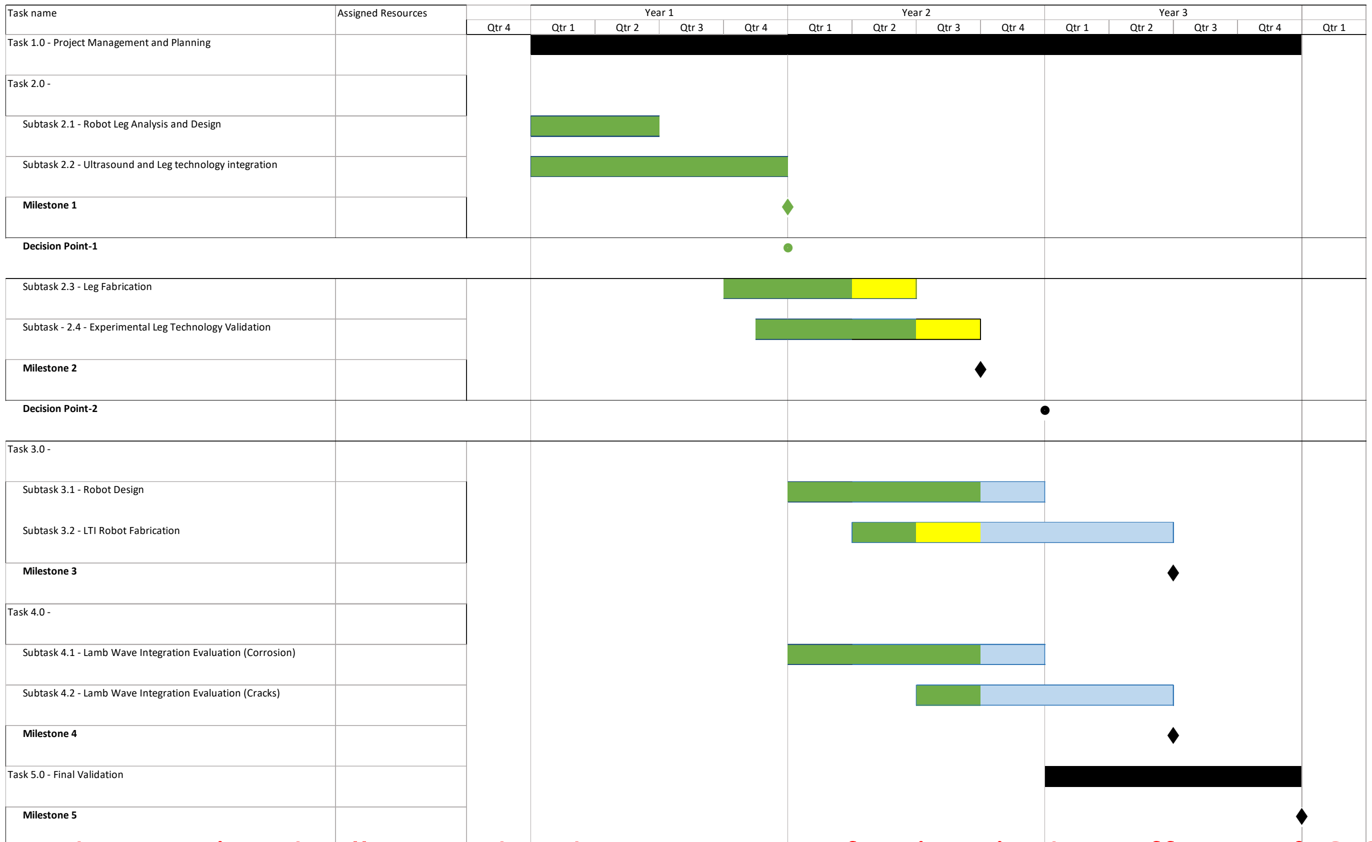
Carryout the Strategic Petroleum Reserve Life Extension Phase II Project

FE will carry out the SPR Life Extension Phase II (LE2) Project to ensure short-term and long-term operational effectiveness and modernize aging SPR infrastructure through systems upgrades and associated equipment replacement. FE will execute the LE2 Project while continuing to operate in order to protect the Nation from potential supply disruptions and meet requirements under the International Energy Program.

Cultivate and maintain a highly qualified, diverse, and well-trained workforce capable of achieving the FE mission and objectives

The FE workforce is facing three challenges. First, the workforce is aging and increasingly eligible for retirement. In FY 2018, approximately 22 percent of the FE workforce was eligible for voluntary retirement.

Challenges, current status and next steps



The main challenge both teams are facing is the effect of COVID19 on operation of laboratories at NMSU and ASU

Next steps: 1. Manufacturing 2 LTI robots (one at NMSU and one at ASU), 2. Integrating the entire EMAT sensing system and 3. Continue performing the fundamental research on friction based Lamb wave excitation, 4. finalize ultrasound imaging, and 5. Creating a testbed (e.g. pipelines/tubes with internal defects) at ISNDE laboratory at NMSU for final test and validation of LTI.

Materials Evaluation special issue

Robotic Inspection

Call for Papers on Robotic Inspection

Materials Evaluation invites interested researchers to contribute to our upcoming Technical Focus Issue on Robotic Inspection, to be published in July 2021. To submit an abstract for consideration, please contact **Dr. Ehsan Dehghan-Niri**, Ph.D., guest technical editor, at niri@nmsu.edu. Final manuscripts for invited papers must be submitted no later than December 1st 2020.

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Q&A

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