Development of a Pipe Crawler Inspection Tool for Fossil Energy Power Plants

NATIONAL ENERGY TECHNOLOGY LABORATORY

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FIU

Project Description and Objectives

Typical Power Plant Inspections

- Challenging and time consuming
- Manual and external
- Conditions sometimes unsafe for humans
- Difficult/impossible to access areas

Present Research Work

- Robotic inspection as an alternative to monitor the structural health of plant components
- Improves capabilities of the fossil energy community to better understand the health of critical components in their infrastructure
- Reduces plant down time, increasing efficiency and cost savings

Project Description and Objectives

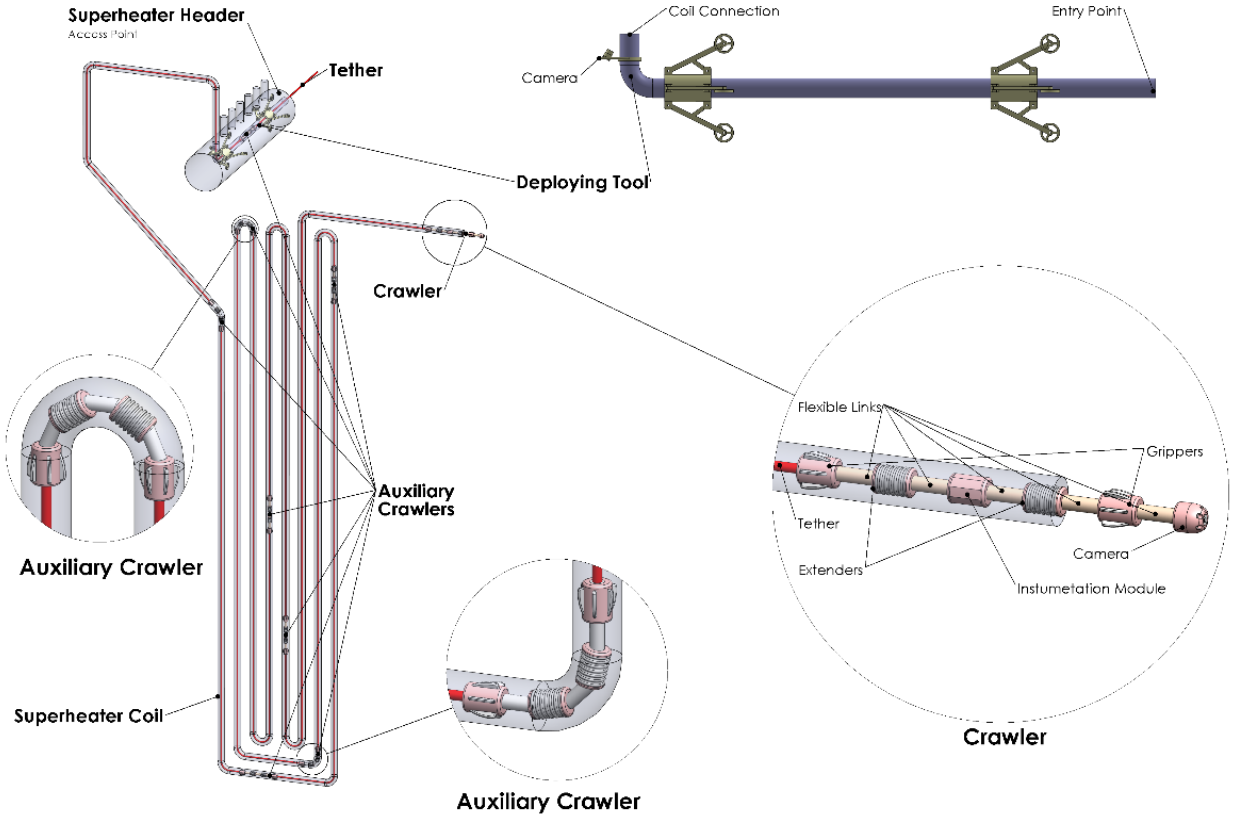
- The objective of the proposed project is to develop a robotic inspection tool that can provide information regarding the structural integrity of key pipeline components in fossil fuel power plants that are not easily accessible.

- The proposed system consists of a tethered pipe crawler that can navigate through 2 inch diameter pipes typically found in the boilers of fossil power plants.
- The primary system will also house sensors that can be used to determine the state of the health of the pipes. The sensor suite includes an optical camera, LiDAR (light detection and ranging) and ultrasonic transducer (UT) sensors that can be used to obtain thickness measurements of the pipes.

Project Description and Objectives

- Utilize lessons learned from previous pipe crawler and inspection tools
- System will navigate through 180 degree bends
- Multiple systems will be coupled together to distribute tether load
- Deploying mechanism through the header

Superheater Header & Tubes

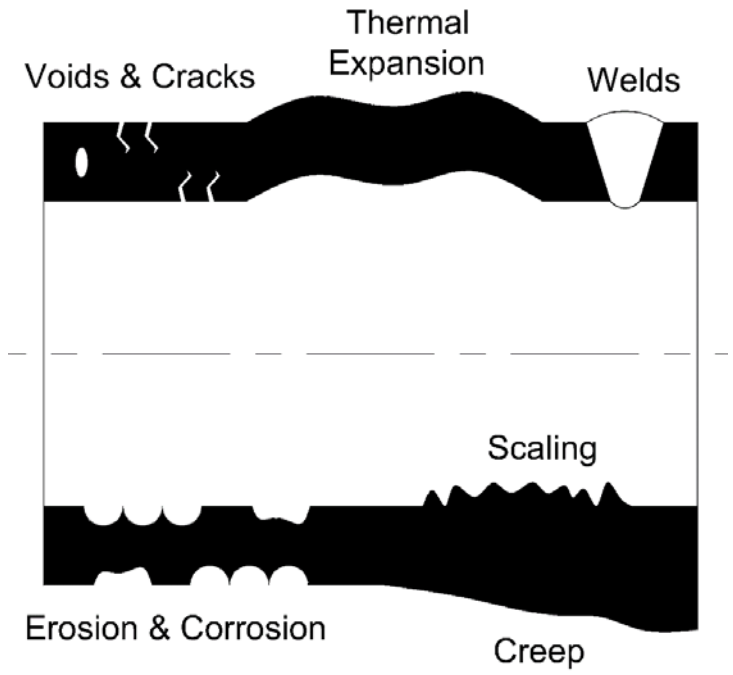


Inspection Tool Operation

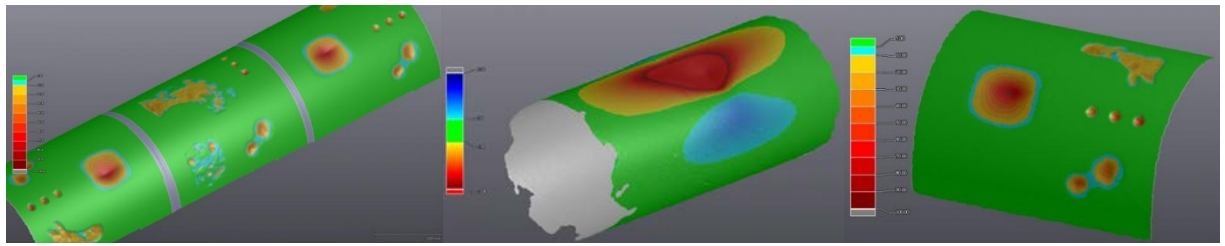
Project Description and Objectives

Inspection Tool Concept

- Sensors will be incorporated into a sensor module to detect pipe irregularities
- The module is customizable and will include an optical camera, IMU, range finder (LiDAR)
- Visual inspection of interior surface – anomalies in pipe, scaling, wear, weld seams
- An additional module will include a UT sensor for surface preparation and thickness measurements.



Surface mapping



Project Description and Objectives

Tasks to be Performed

Task 1.0 - Project Management and Planning
Task 2.0 - Robotic Crawler Development
- Subtask 2.1 – Conceptual design of modules
- Subtask 2.2 – Manufacturing and testing of modules
- Subtask 2.3 – Assembly and initial testing

Task 3.0 – UT Sensor Analysis
- Subtask 3.1 – UT Sensor Evaluation
- Subtask 3.2 – UT Sensor Requirements

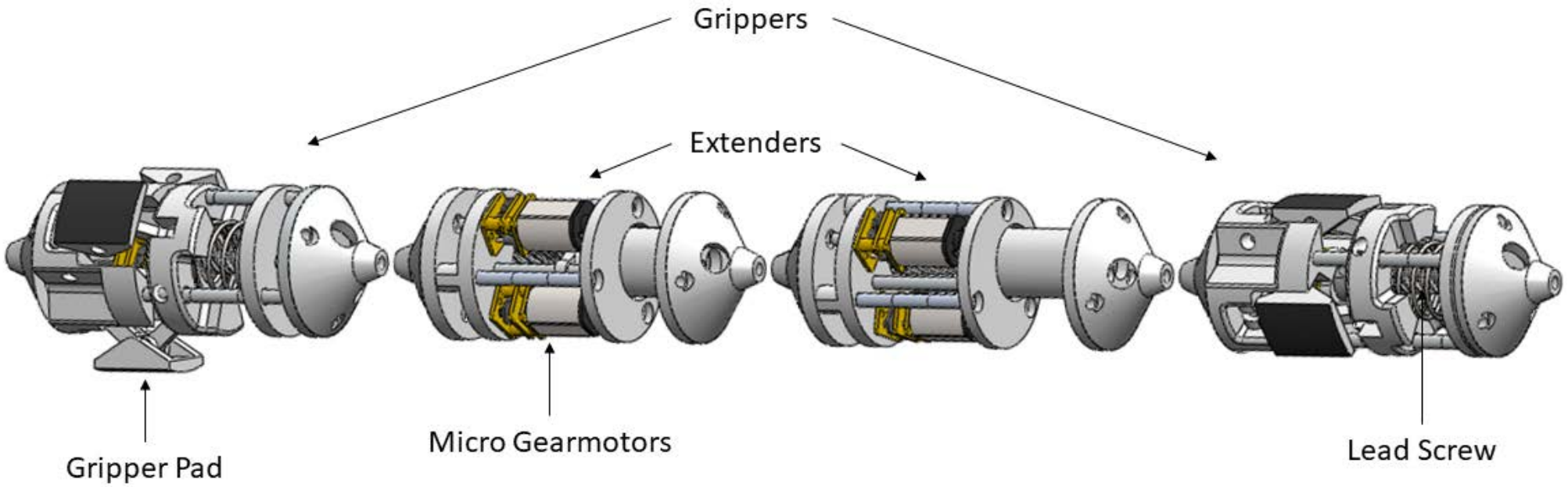
Task 4.0 – Sensor Module Development
- Subtask 4.1 – UT sensor module
- Subtask 4.2 – LiDAR sensor module

Task 5.0 – System Integration
- Subtask 5.1 – Multiple crawler design and integration
- Subtask 5.2 – Power and instrumentation control/communication

→ Task 6.0 – Full Scale Testing

Project Update

Moving Platform



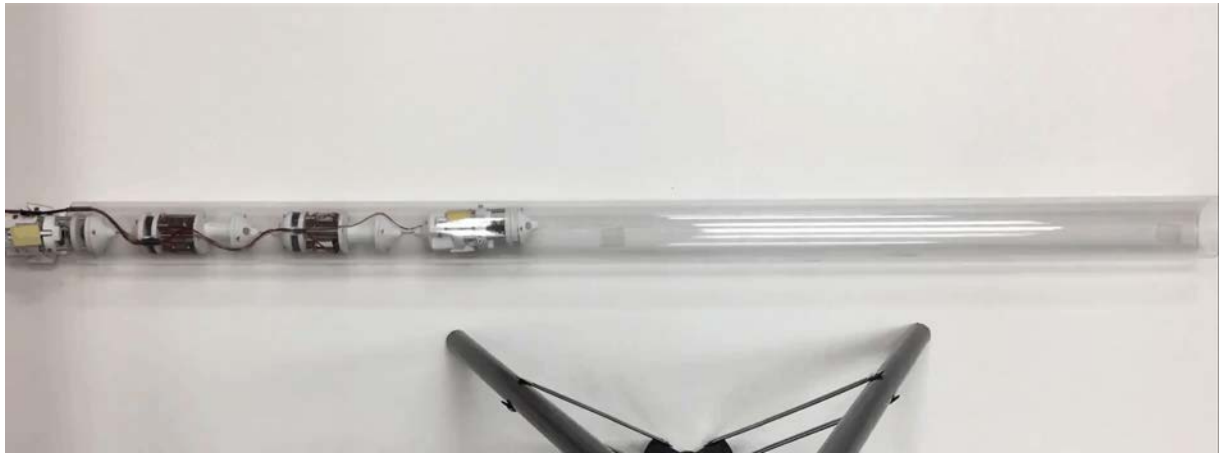
Peristaltic Motion to Travel Through Pipe

- Extender modules expand and contract linearly
- Linear actuation controlled by rotating lead screw
- A 3D printed prototype has been developed with nylon, tough PLA, polycarbonate

Project Update

Moving Platform

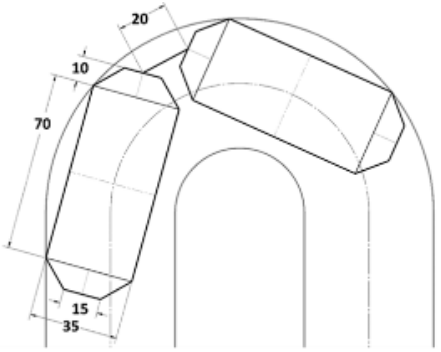
Straight Pipe Section Test



180-degree Bend test

Challenges

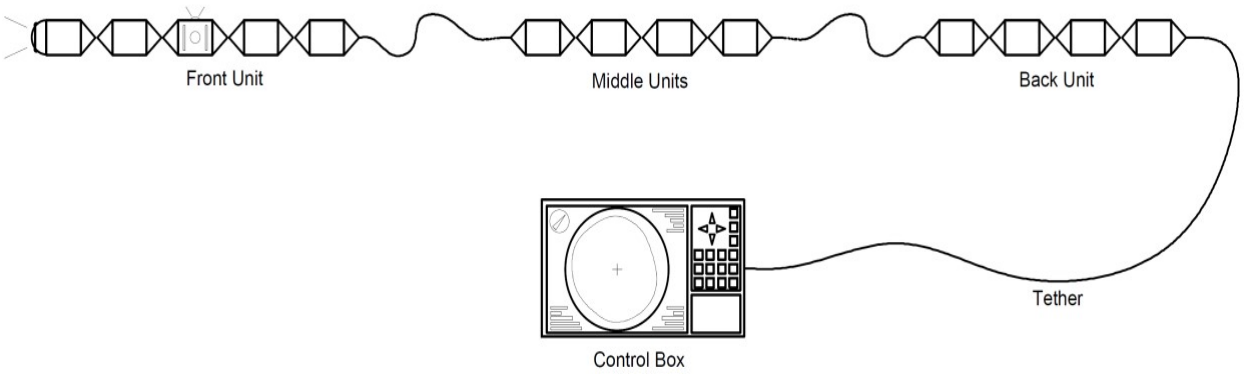
- Wire management
- Maximizing pull-force (current force is ~9 lbs)
- Finding appropriate dimensions for sharp turns

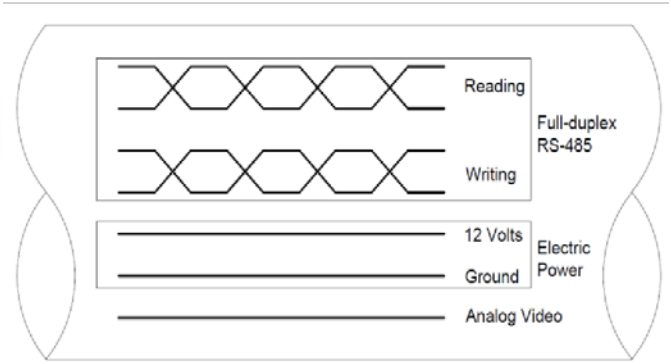


Project Update

Electronics and Communication System

- The peristaltic movement is fully automated and remotely controlled.
- Each unit will contain at least one microcontroller and others may be added for the sensors.
- The movement of each module is controlled by sensing the electrical current in the motors
- Long-distance communication tether to the crawler via serial network

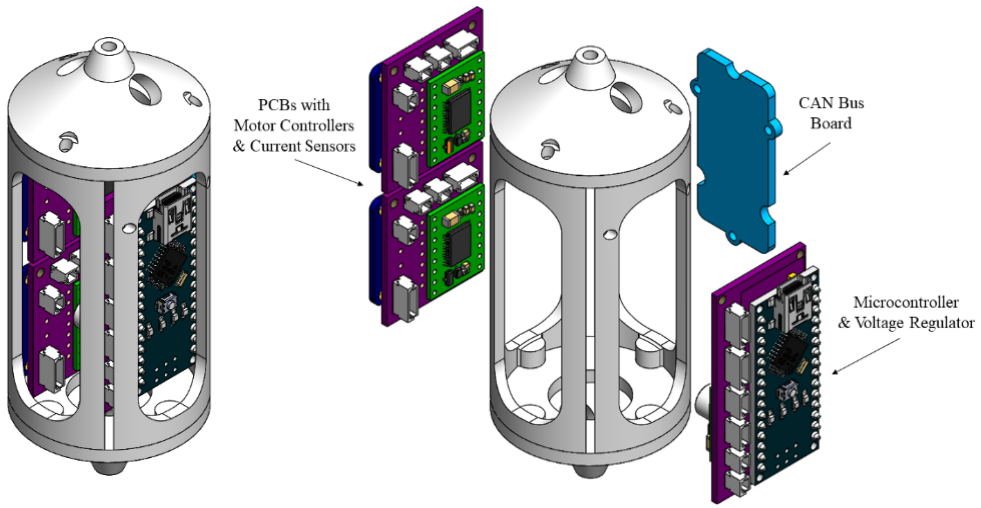


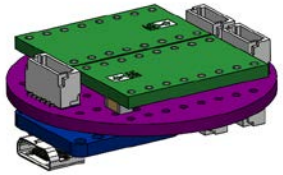


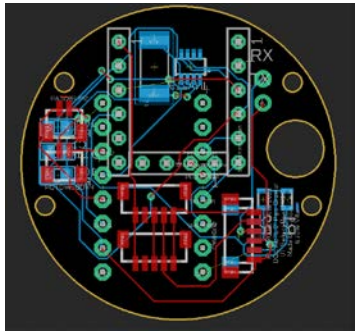
Project Update

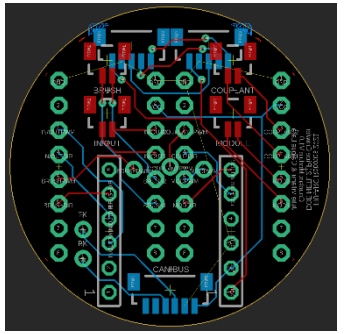
Electronics and Communication System

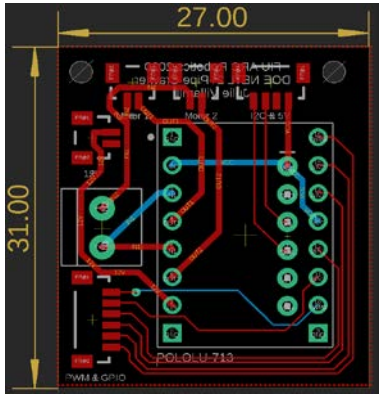
- Development of printed circuit boards (PCBs) to mount the electronics
- PCBs have been designed to house the receiver chips, microcontrollers, and voltage regulators
- Electronics module is currently being developed.
- Slip ring for rotating sensor modules

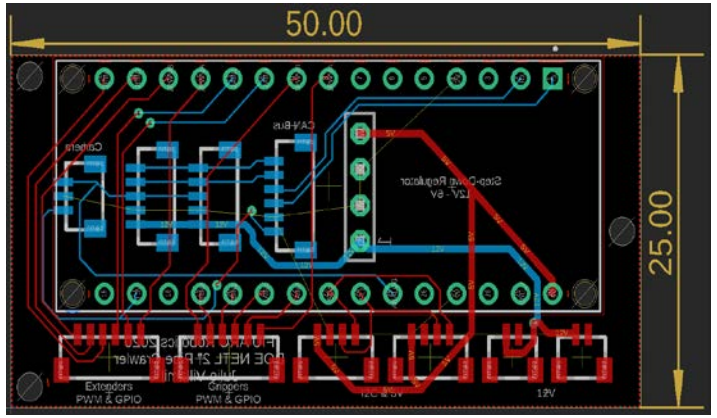






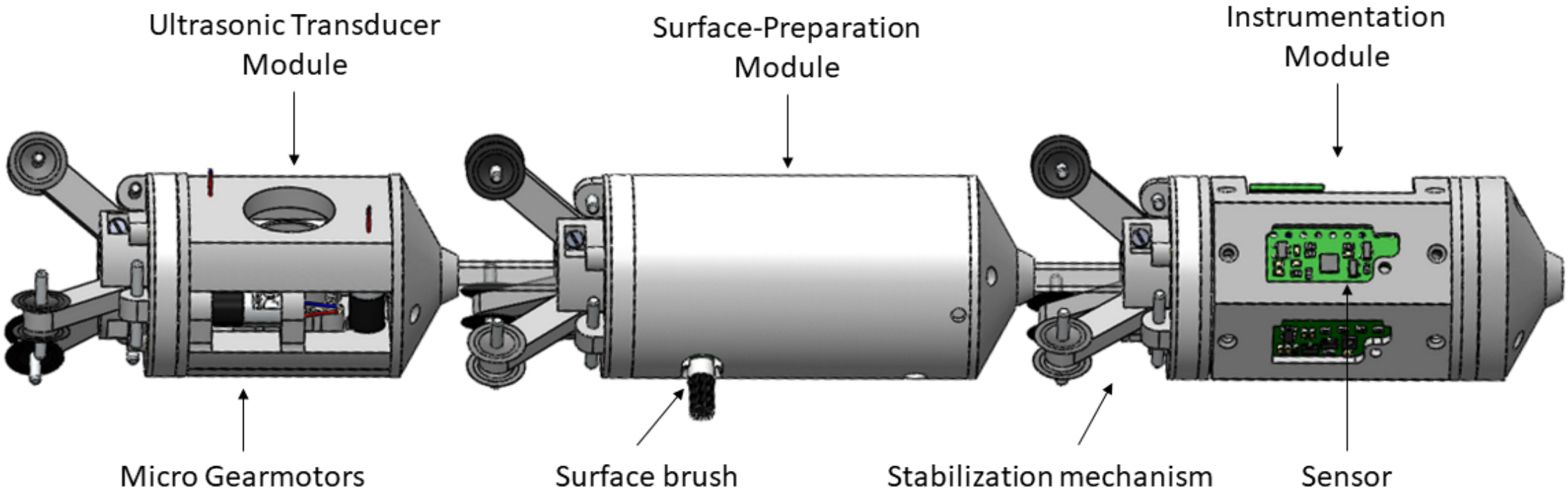






Project Update

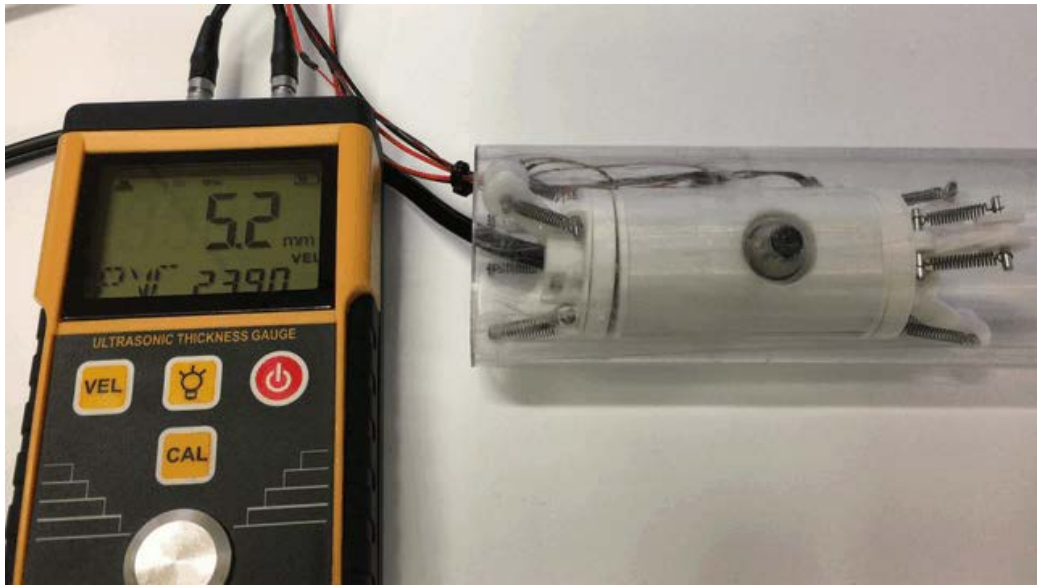
Sensor Modules



Project Update

UT Sensor Module

- UT sensor module includes an ultrasonic probe for wall thickness measurements
- Module contains a linear actuator that provides the prismatic movement of the UT sensor probe

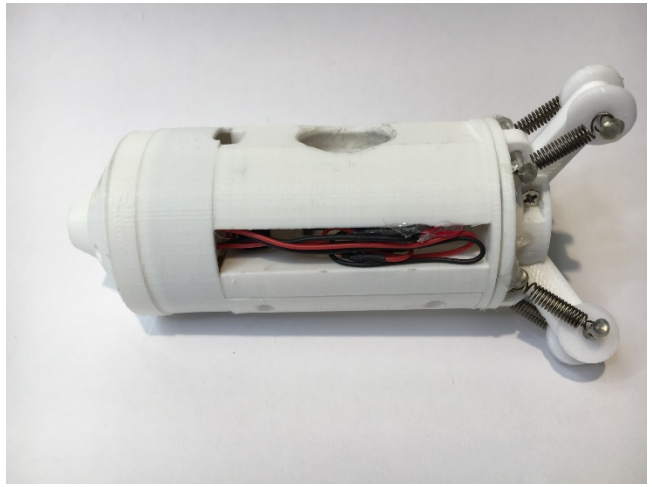


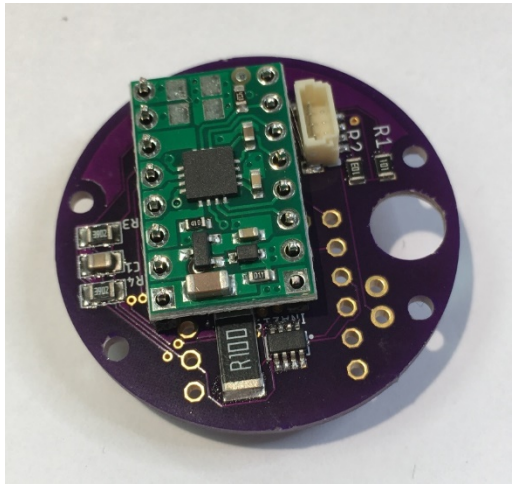
Project Update

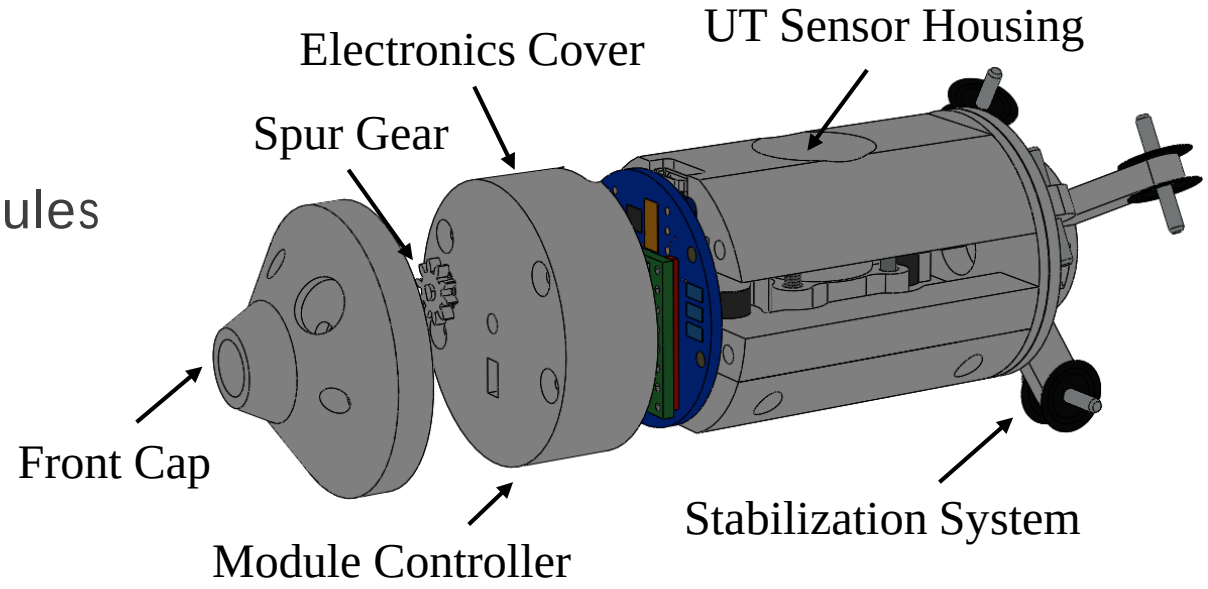
UT Sensor Module

Updates

- Printed Circuit Board (PCB) connect the microcontroller to sensor and motors
- Control unit integrated to the front-end
- Uses CAN-Bus to communicate with other modules



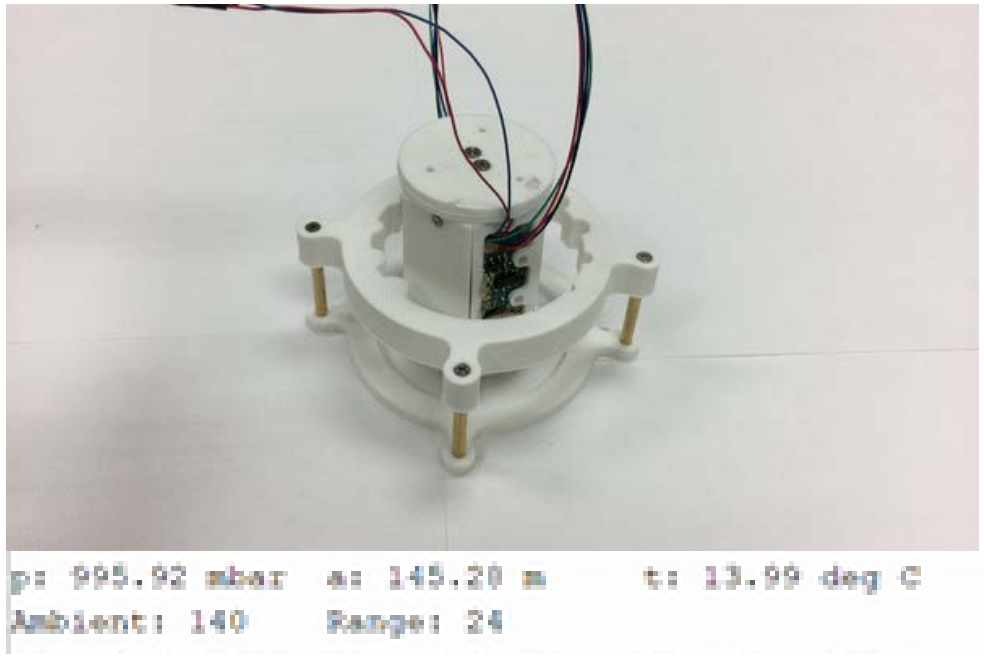


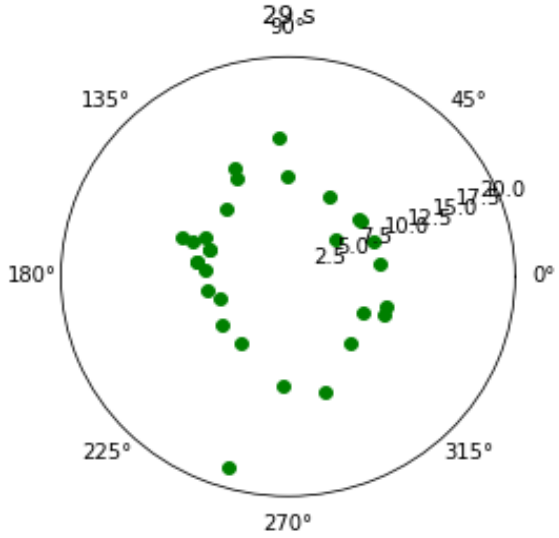


Project Update

Instrumentation Module

- Evaluates the internal surface of the pipe and includes 3 sensors: LiDAR, IMU, and environmental
- Carrousel-like device that rotates with a planetary and spur gear set



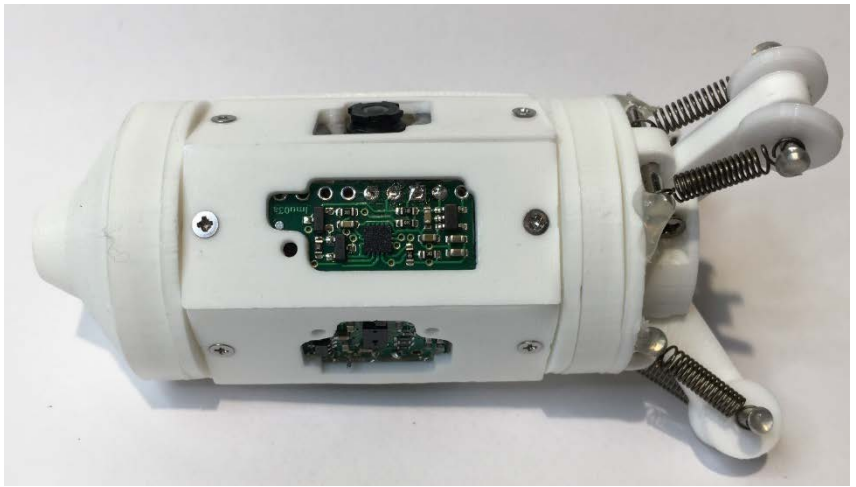


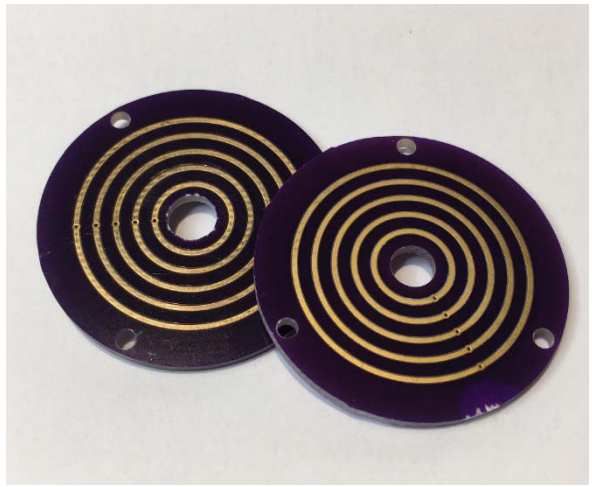
Project Update

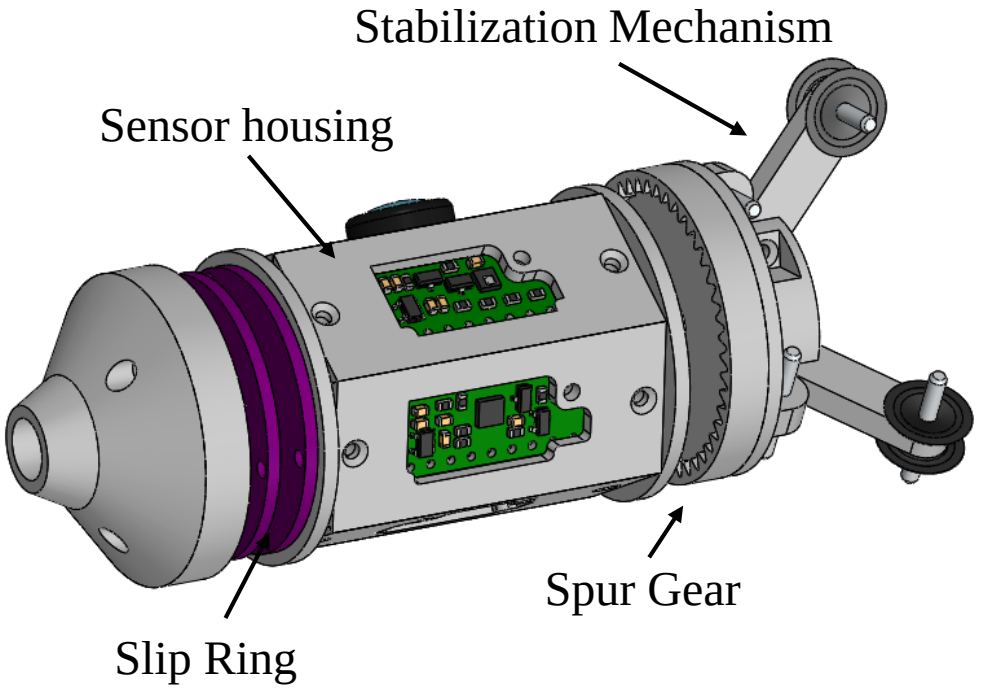
Instrumentation Module

Updates

- A Slip Ring was developed to enhance the wire management during rotation
- A PCB connect the sensors with the microcontroller
- Communicate with other modules using CAN-Bus







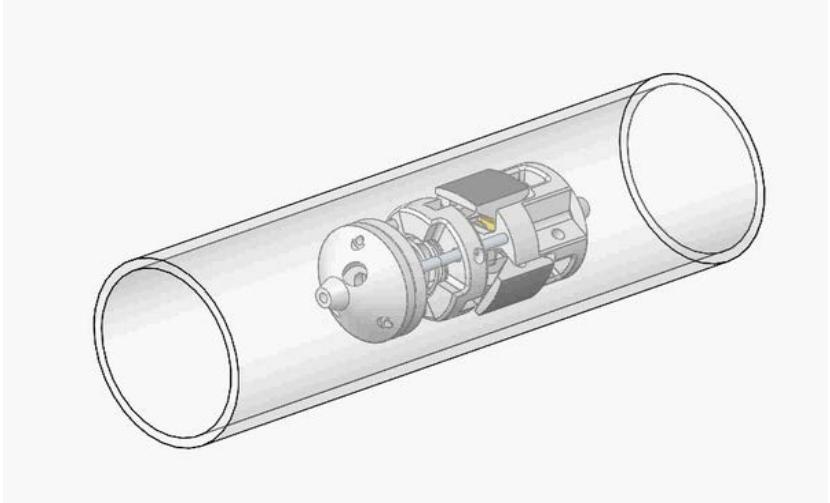
Project Update

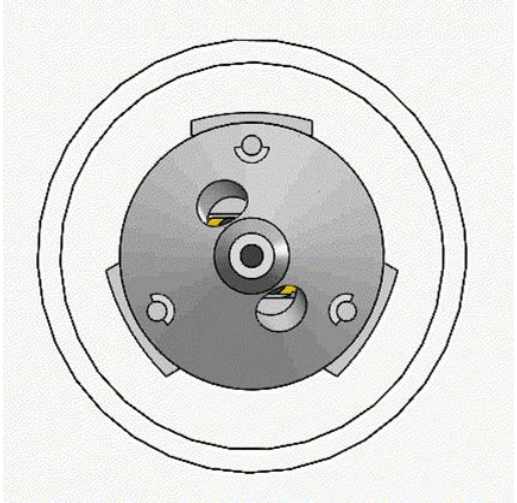
Development of High Fidelity Simulation Model

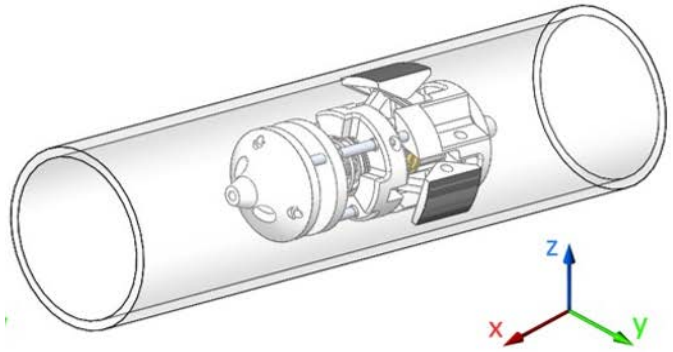
- Effort are being made to generate a high fidelity simulation of the crawler that will provide a platform to analyze different aspects and control strategies, virtually.

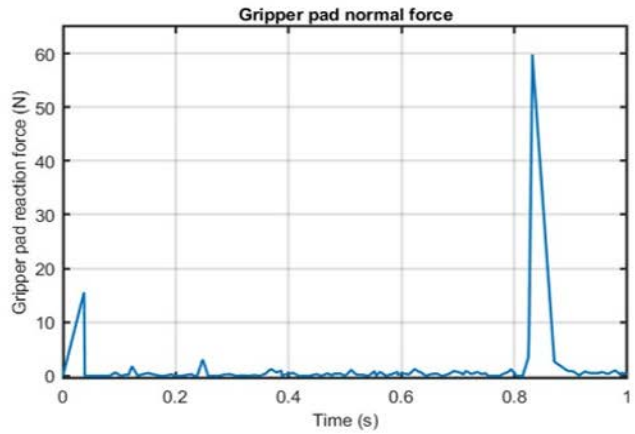
- Initially, a basic motion analysis, was conducted in SOLIDWORKS. Gripper and extender modules were generated and simulated.

- The force of contact between the gripper pads and the tube was analyzed to find the pull force of the gripper, that holds the tube when the gripper pads are extended.



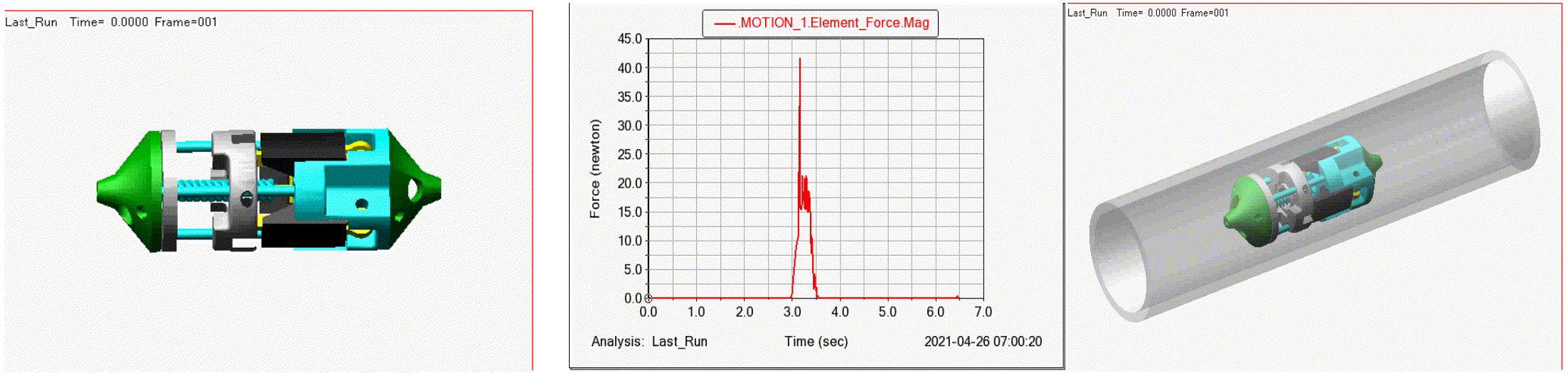






Project Update

Development of High Fidelity Simulation Model



Dynamic motion analysis of gripper

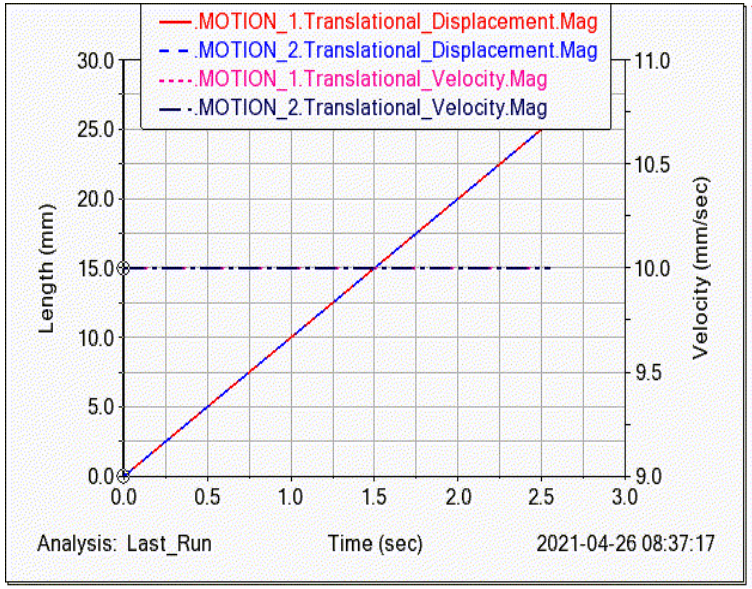
- Efforts switched to utilizing ADAMS which is a Multibody Dynamic Motion Simulation Software, to analyze and perform the high-fidelity virtual simulation.

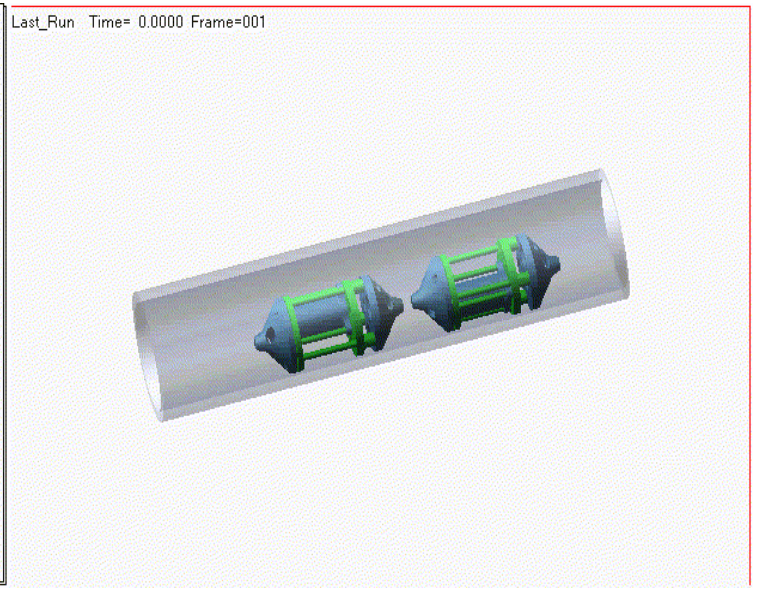
- ADAMS provides a larger database of tools and functionality which will be useful in developing a control strategy for the high-fidelity simulation.

Project Update

- A motion analysis of both extenders was conducted in ADAMS. The simulation was designed to have a maximum extension of 25 mm and a constant operating speed of 10 mm/sec.

- The extension/retraction of the extenders occurs after either the rear gripper or front gripper engages the pipe wall.



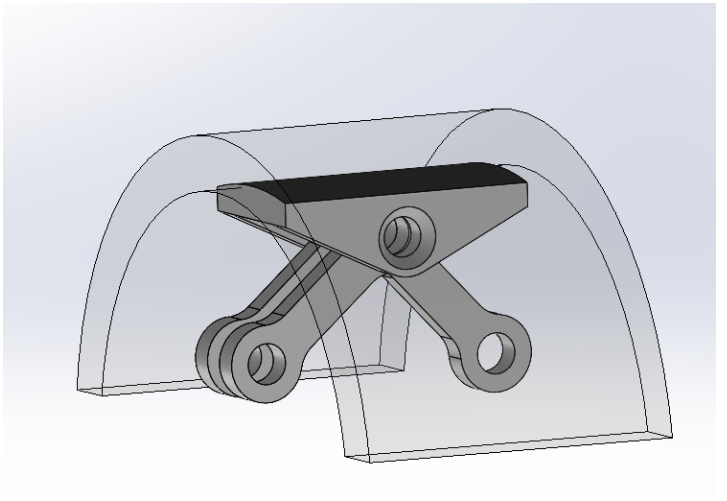


Motion analysis of Extender in ADAMS

- A complete simulation of the combined grippers and extenders will be performed using MATLAB/Simulink with ADAMS to implement control strategies.

Project Update

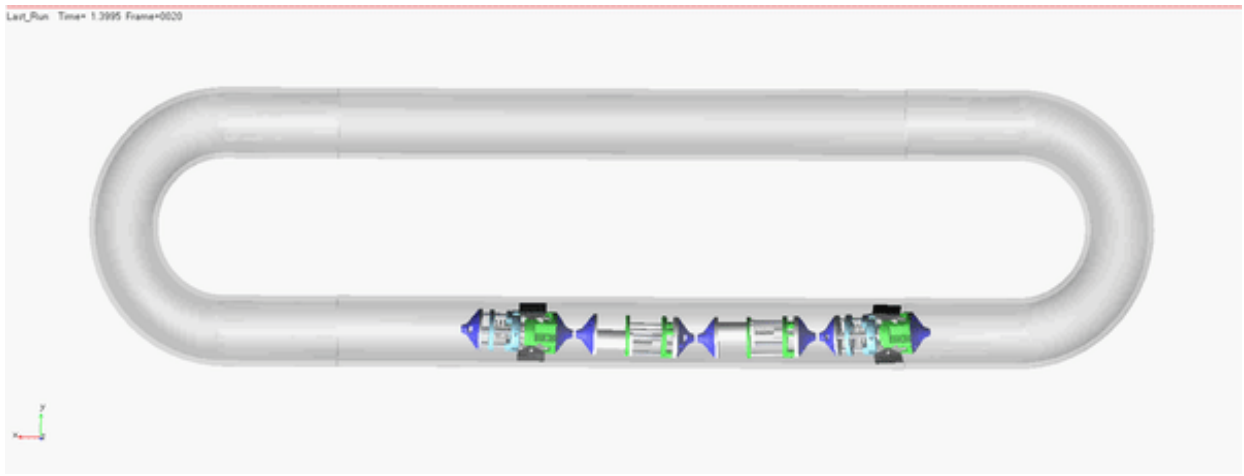
- One of the major objectives is to accurately simulate the pull force of the crawler system. This is dictated by the pull force of the extender module and the gripping force of the gripper module.
- The gripping force depends on the friction and normal force between the gripper pad and the pipe.
- Factors and properties of the contact force that affect the simulation include:
  - -Stiffness coefficient, force exponent, damping coefficient
  - - Penetration depth and the friction coefficient



Gripper pad in a small section of pipe

Project Update

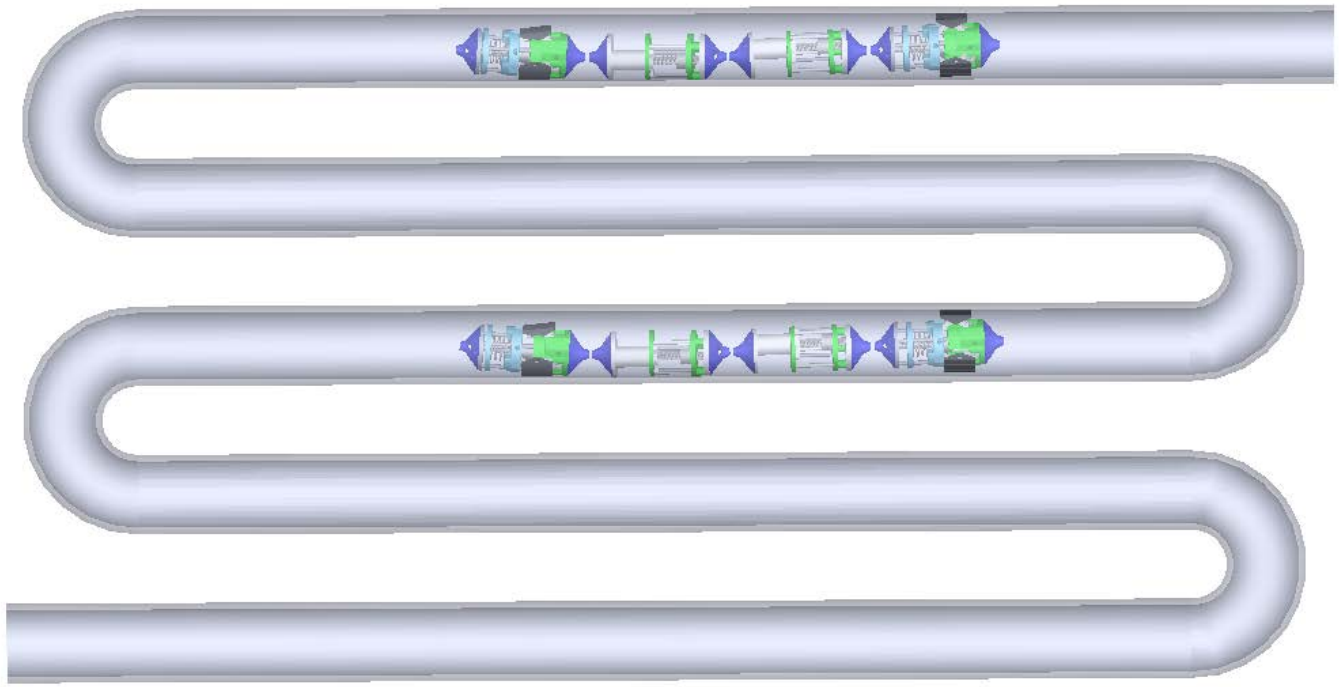
- A motion simulation of the crawler (gripper and extender modules) has been conducted for the straight section.
- Currently investigating numerical issues related to contact forces during bends.
- A control strategy is being developed to optimize the high-fidelity simulation that will assist in maximizing the pull force of the multi-crawler system.



Motion simulation of the pipe crawler

Project Update

- A motion analysis of two crawlers is being conducted simultaneously .
- A clear mock-up is being used for the motion simulation of both the crawlers.
- Currently working on the communication system between the crawlers to control the speed between them.



Motion simulation of the pipe crawler

Project Update

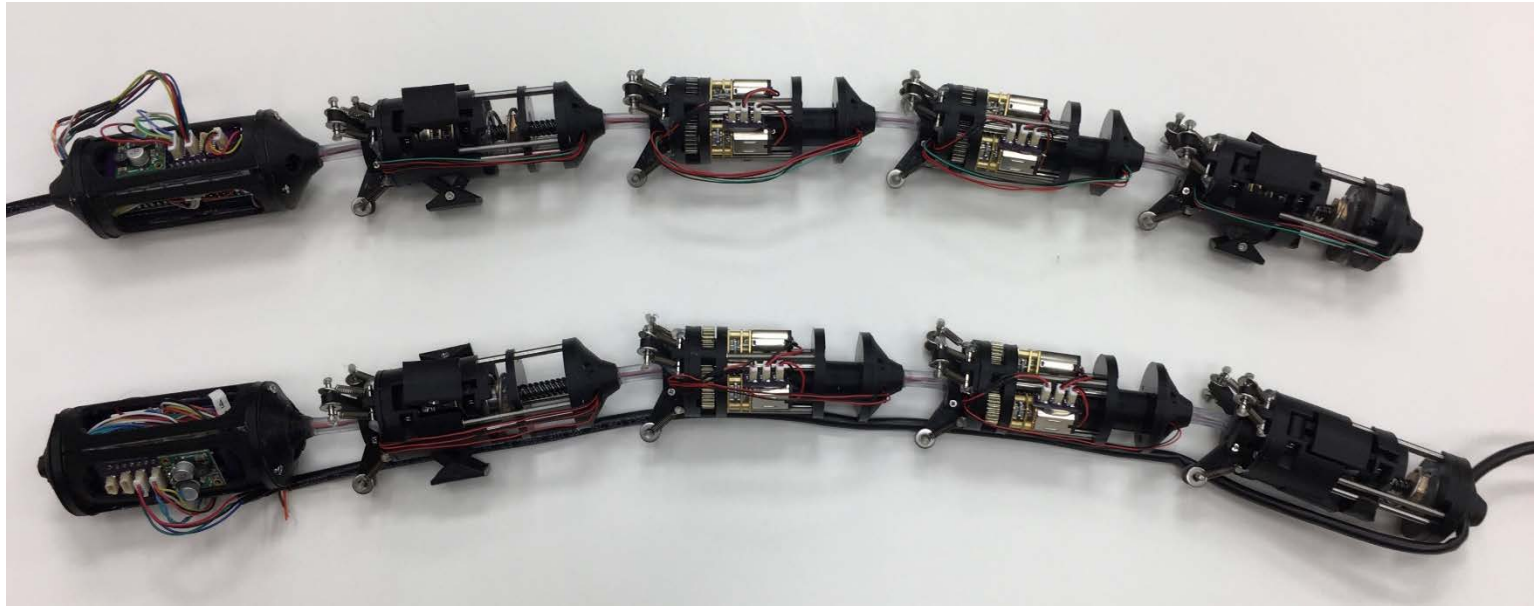
Engineering Scale Testing

- 2- inch Mockup for evaluation of tether loads using clear PVC for visualization. A similar metal mockup is currently being constructed.
- Determine optimal strategies for multiple crawlers to distribute the tether load.

Project Update

Multi Crawler System

- Development of second crawler
- Integration of communication system for all modules
- Daisy-chained via front and back end of crawlers



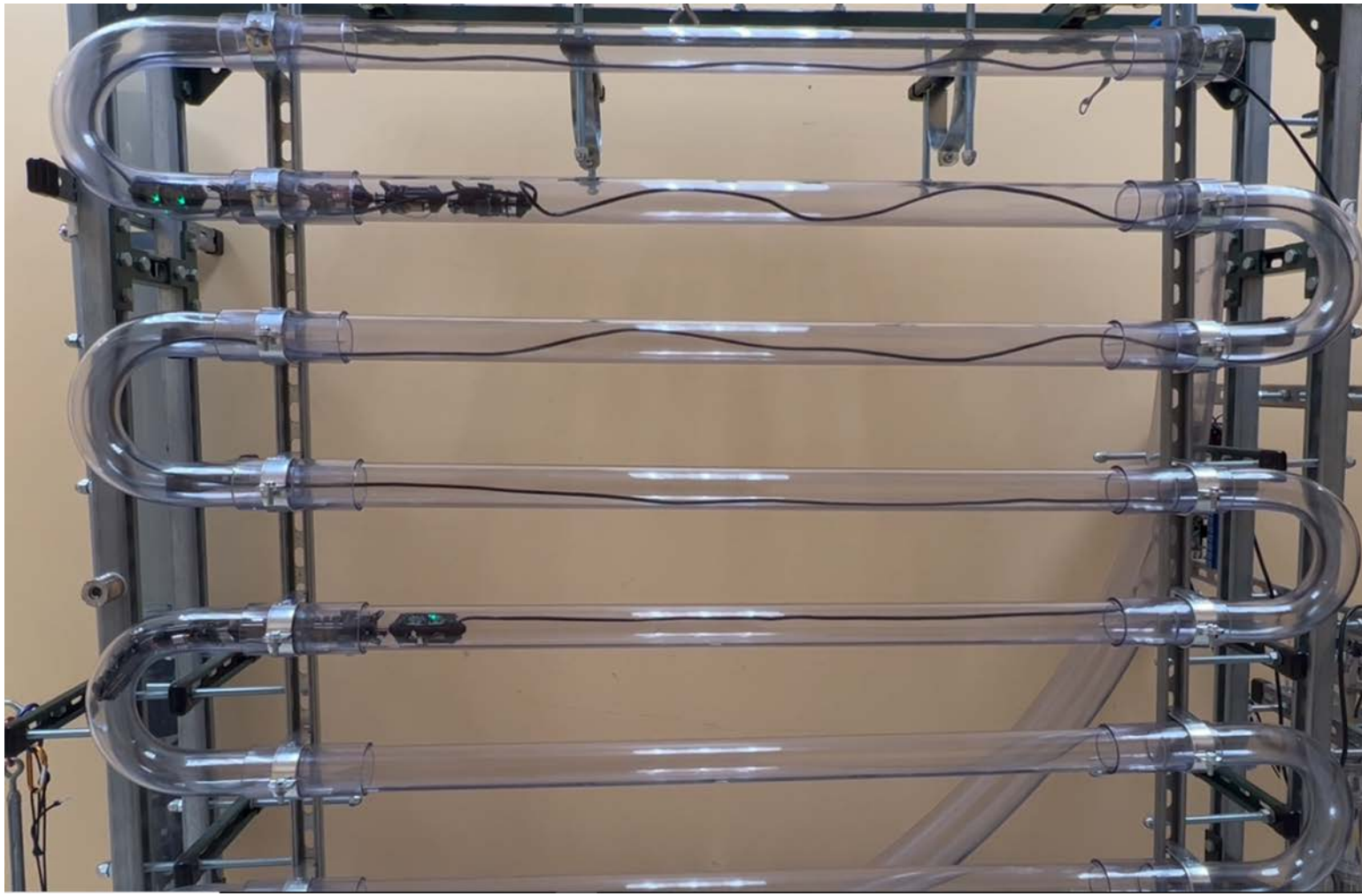
Project Update

Engineering scale testing

- Testing of the two crawler system to extend the inspection capability of the tool

Future plans

- Durability evaluation
- Tether force control
  - Addition of force transducers in between the crawlers
  - Develop control strategy for keep the tension in the tether constant



Preparing Project for Next Steps

Market Benefits/Assessment

- Current technologies are limited in their abilities to provide thickness measurements and other data related to the structural health of complex piping systems with small diameters similar to those found in fossil energy power plants.
- This research effort bridges the gap for these inspections and can reduce plant down time and increase plant efficiency while keeping employees out of harms way.

Technology-to-Market Path

- The inspection tool developed in this research effort demonstrates the concept of a semi-autonomous system that achieves a mid-level TRL (technical readiness level). Working with engineers at power plants will assist in it's continued development and ultimately, demonstration and testing in the field.
- Additional research areas include developing a deployment mechanism specific to a facility and improving reliability with custom design components.
- Collaborators are needed for the demonstration of the system. Currently, we are working with engineers at Portland General Electric.

Concluding Remarks

- FIU has developed a multi-crawler system that can navigate through 2 inch diameter piping systems with multiple 180 and 90 degree turns – typical of fossil energy power plant super-heater tubes.
- The crawlers are modular and include sensors for thickness measurements as well as anomaly detection in the tubes.
- Technical challenges include durability assessment of components/ modules, wire and tether management and maximizing the pull force.
- The crawler has been used as a case study to assist in the development of a standard with ASME's Crawlers for Inspection Committee
- Article recently published in *Materials Evaluation* titled, "Development of an Innovative Inspection Tool for Super-heater Tubes in Fossil Energy Power Plants"

Concluding Remarks

- Julie Villamil won 1st place at FIU's MME Undergraduate Research Symposium
- "Robotic and Sensor Systems for Infrastructure Inspection", ASME Power Conference and Nuclear Forum, Drone and Robotics Seminar, Salt Lake City, UT, July 18, 2019.
- "Robotic and Sensor Systems for Infrastructure Inspection", ASME Power Conference and Nuclear Forum, Drone and Robotics Seminar, Virtual, August 4-5, 2020.

Acknowledgment & Disclaimer

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