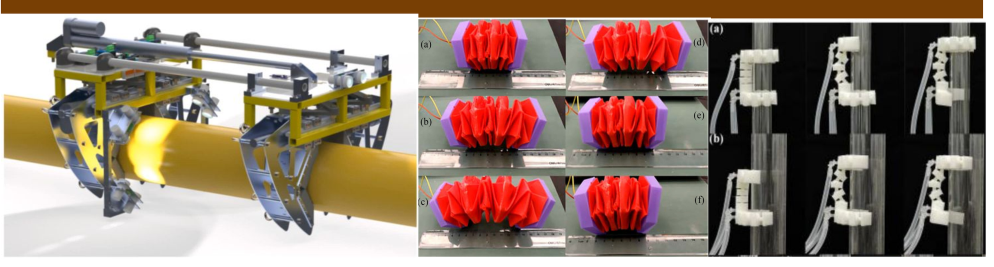
The Creation of SPIRo: An AI Based Origami Inspired Soft Robot with Multidimensional Locomotion for Infrastructure Assessments

Issue Statement

- Infrastructure failures are becoming increasingly common and are affecting more people and environment
  - Public Facilities - Pipelines, cranes, bridges
  - Military Infrastructure - Aircraft carriers, nuclear reactors
  - Complex Structures - Aircraft, spacecraft launchpads
- Specifically, serious gas leaks occur every 40 hours in the US and explosions cause millions of dollars in damages and 700 injuries/fatalities [1]
- 2.6 million tons of methane, a greenhouse gas 30 times more potent than CO2, is leaked from US pipelines annually. [2]

Previous Research



Top Left: Hard out of pipe robot for riser cable inspection [3]
Top Center: Origami inspired soft robot [4]
Top Right: Soft robot designed for curved surfaces [5]
Attallah: Fusion of Gas Sensors and Thermal Images [6]
Kobpayev: Implementation of Random Forest for fusion of spatio-temporal data [7]
Zhou: Deep Forest Classifier Development for Multimodal Ensemble Learning [8]

Research Gaps and Solution

Gap	Solution
Internal pipe robots disrupt pipe usage	Out of pipe design enabling continuous inspection
External pipe robots are bulky and slow	Soft robots for increased flexibility and compactness
Soft robots unable to locomote quickly	Individually actuated McKibben Muscle actuators for complex deformation and faster speed
Unable to carry payloads necessary for inspections	Strong McKibben muscle actuators enabling heavier payloads
Fit in tight spaces and still grip to pipes	Origami inspired pouch motor magnetic feet to attach to pipe
Lack of machine learning algorithms with high accuracy and redundancy for gas leak	Use of multimodal ensemble deep forest learning for increased accuracy, redundancy

Design Criteria & Constraints

Criteria	Constraints
Horizontal Crawling Speed of 10 mm/s and Vertical Climbing Speed of 5 mm/s	Requires externally mounted air compressor and microcontroller
Weighs no more than 250g and is no larger than 500 mm x 70 mm x 80 mm	Needs extensive pneumatic tubing for inflation of individual extensional actuators
Body deforms 45 degrees vertically and 30 degrees laterally for navigating around obstacles	Difficulty navigating more intricate and complex structures.
Magnetic gripper to attach to any radius of pipe at any angle	Requires magnetic or ferromagnetic surfaces to grip
Multimodal data collection system to enhance accuracy, redundancy, and efficiency	Microcontroller needs sufficient memory and speed for simultaneous ML model and valve control
Target leak detection accuracy of 90% for training and 70% for in field testing	Finding field testing site for data collection of all modes

SPIRo System Design and Development Timeline

Design — June 15 - July 30
- Extensive literature review and decide system architecture and components
- Initial CAD design according to design criteria
- Investigate leak detection methods and past solutions

Gen 1 — August 1 - October 10
- Achieves horizontal speed of 9 mm/s
- Pneumatic control circuit setup using MyRIO and pneumatic valves
- Implementation of late fusion of basic CNN and ANN for multimodal gas leak detection

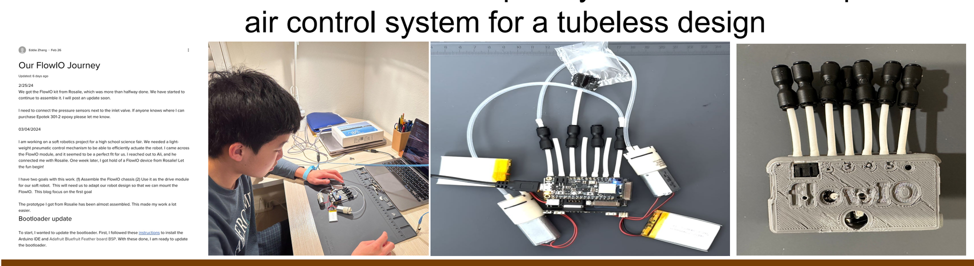
Gen 2 — October 10 - December 10
- Compacted Design of scissor linkage
- Vertical speed of 5 mm/s
- Implement deep forest classification ensemble module for deep feature fusion of multimodal data
- Improved Processing of Thermal Images using three separate CNNs

Gen 3 — December 10 - February 16
- Contractional actuators
- Bending 60º vertically and 40º laterally for steering
- Real-time detection of gas leaks implemented
- Field testing at METEC lab
- Published 2 IEEE conference papers about software and hardware systems of SPIRo

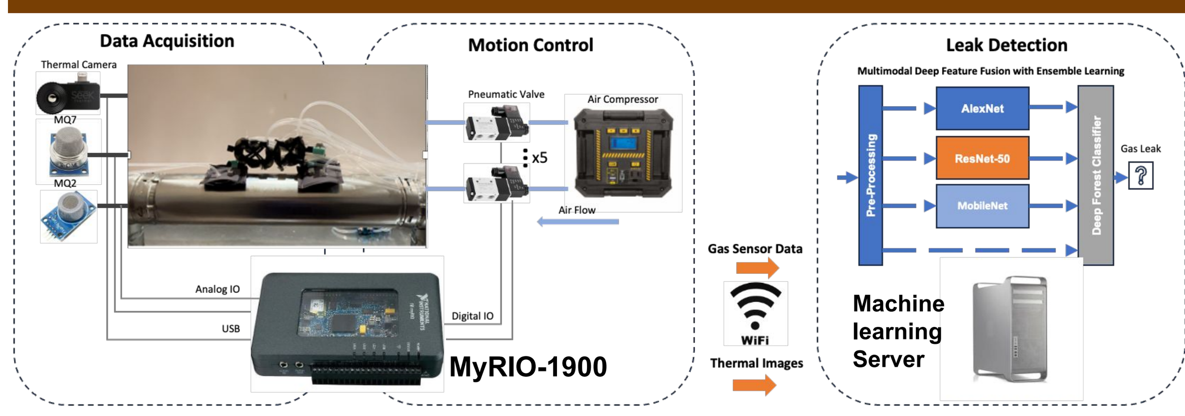
Gen 4 — February 16 - Present

Integration with FlowIO

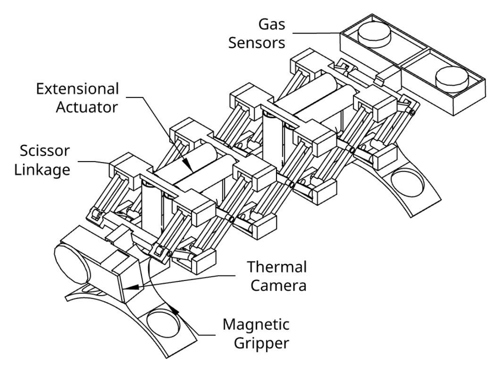
Assembled FlowIO device developed by MIT Media lab for portable air control system for a tubeless design



SPIRo System Design

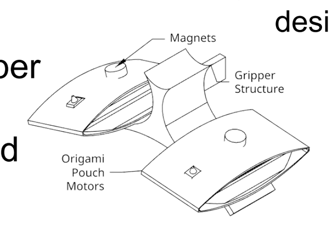


Overall SPIRo motion control, data collection, and machine learning system design flow

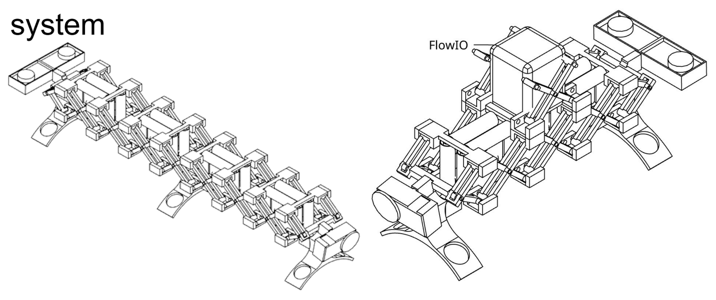


SPIRo's overall design consisting of scissor linkage and actuators

Magnetic Gripper Design with origami inspired pouch motors



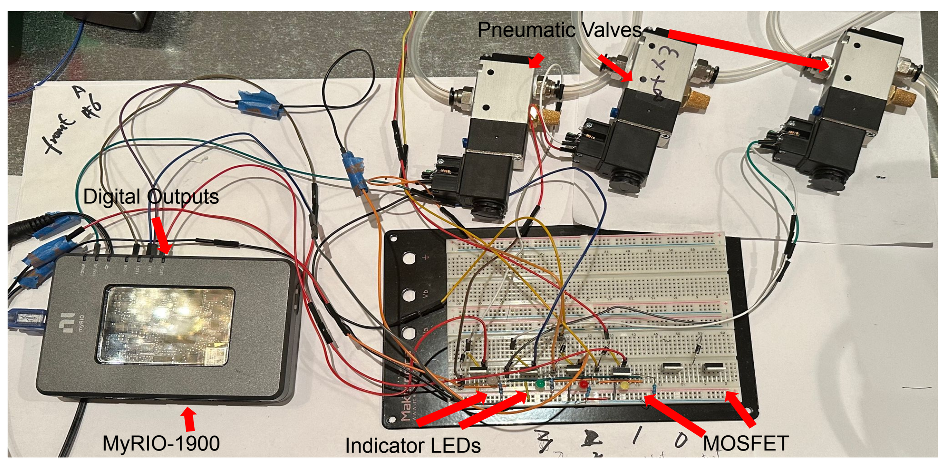
Modular design of SPIRo optimized for longer strides and faster speeds in open areas.



SPIRo depicted with implementation of FlowIO air compressor & valve system

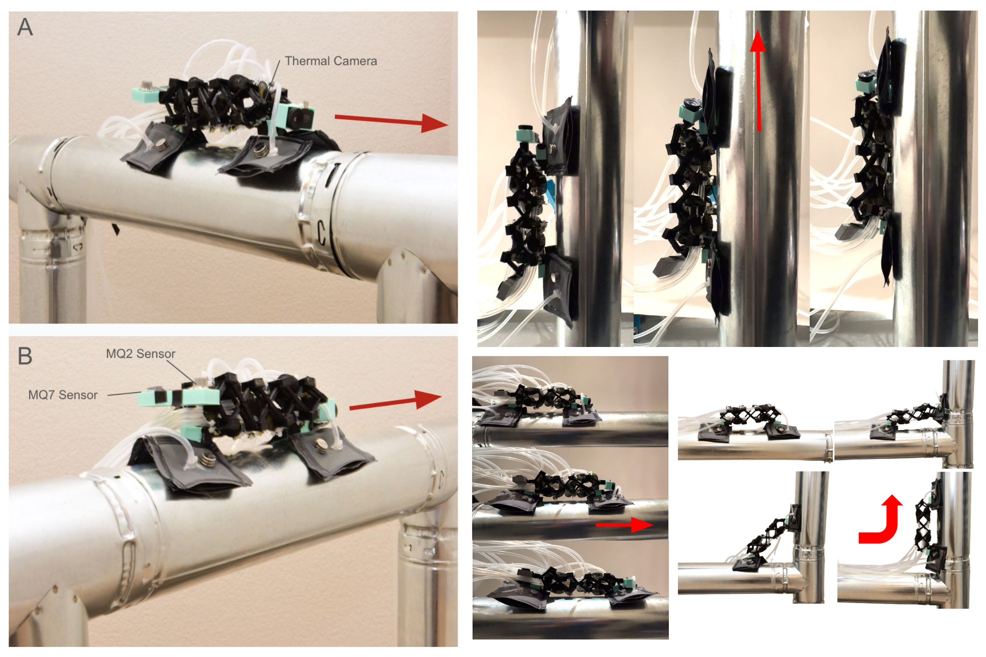
SPIRo Fabrication and Multidimensional Locomotion

SPIRo Pneumatic Control Circuit



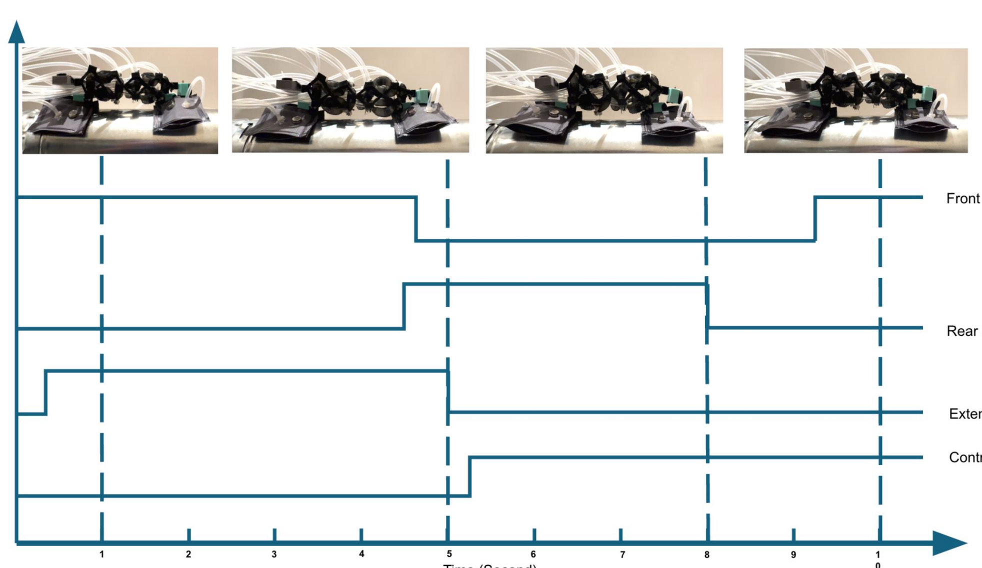
SPIRo 3D Printed and Custom Designed Parts

SPIRo Vertical and Horizontal Locomotion Properties

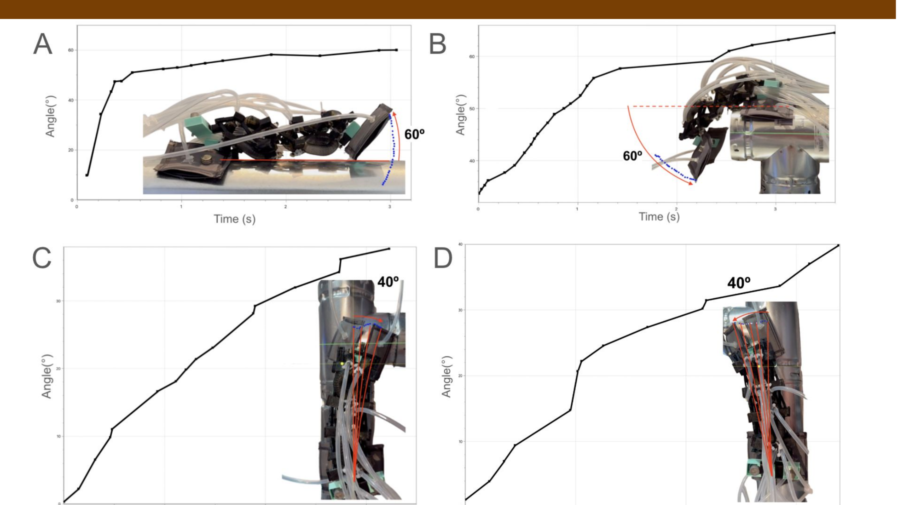


- SPIRo locomotes through individual actuation of actuators for horizontal, vertical and lateral movement
- All of SPIRo's parts are custom designed in CAD and 3D printed

SPIRo Locomotion Timing Pattern



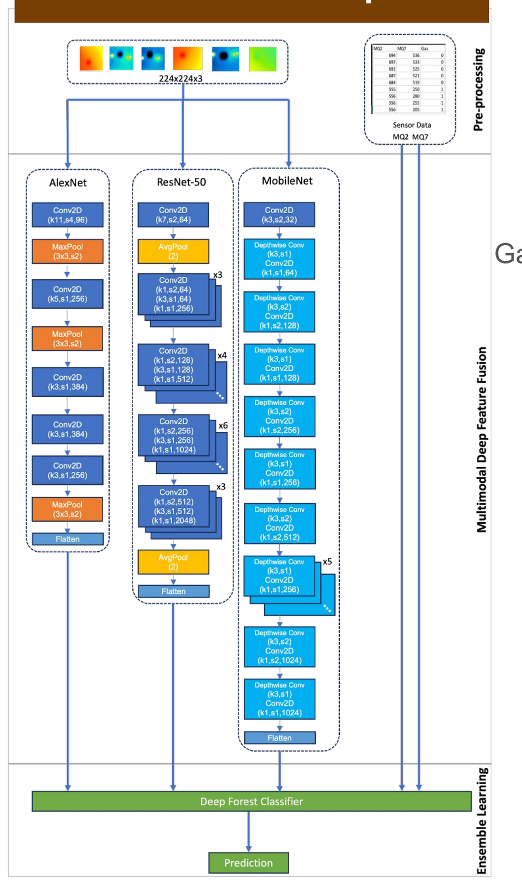
SPIRo Deformation Characteristics



A/B) Vertical Upwards/Downwards deformation up to 60 degrees, C/D) Deformation Laterally up to 40 degrees

Multimodal Ensemble Deep Learning Development

Architecture Development

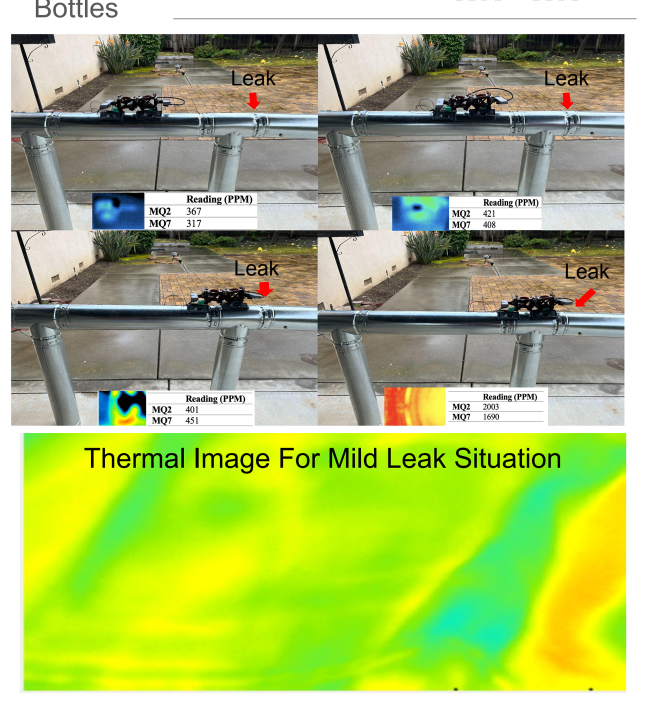


SPIRo Leak Detection Deep Learning System Architecture

Collected Thermal Image and Gas Sensor Data

Gas Calibration Bottles

	Resistance	No Gas	1000 PPM	10000 PPM
MQ2	0.63 kohm	186 PPM	867 PPM	9325 PPM
MQ7	2.72 kohm	179 PPM	799 PPM	8976 PPM



Thermal Image For Mild Leak Situation

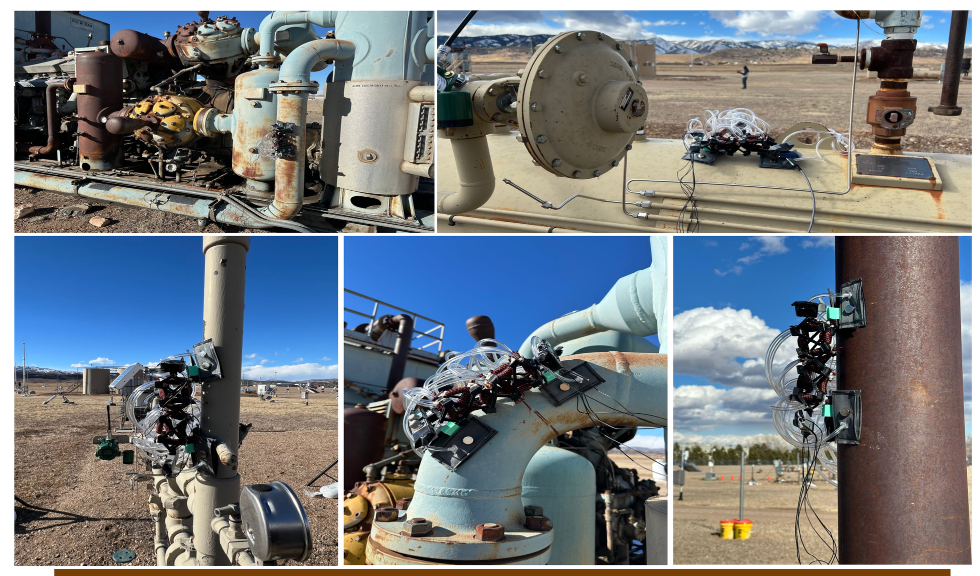
Machine Learning Results

	AlexNet	ResNet-50	MobileNet	Gas Sensors
Ensemble_1	V			V
Ensemble_2		V		V
Ensemble_3			V	V
Ensemble_All	V	V	V	V

		Accuracy	Precision	Recall	F1Score
	AlexNet	0.94	0.93	0.95	0.94
	ResNet-50	0.93	0.93	0.92	0.93
	MobileNet	0.94	0.94	0.93	0.94
Training Data	Gas Data	0.94	1.00	0.88	0.93
	Ensemble 1	0.97	0.99	0.96	0.97
	Ensemble 2	0.93	0.94	0.98	0.95
	Ensemble 3	0.96	0.99	0.94	0.96
	Ensemble_All	0.98	0.99	0.98	0.99
Simulated	Gas Data	0.83	0.76	0.80	0.78
Environment	Ensemble 1	0.84	0.77	0.80	0.78
	Ensemble 2	0.83	0.76	0.79	0.77
	Ensemble 3	0.82	0.74	0.78	0.76
	Ensemble_All	0.88	0.84	0.83	0.83
Field Testing	Ensemble_All	0.77	0.78	0.94	0.85

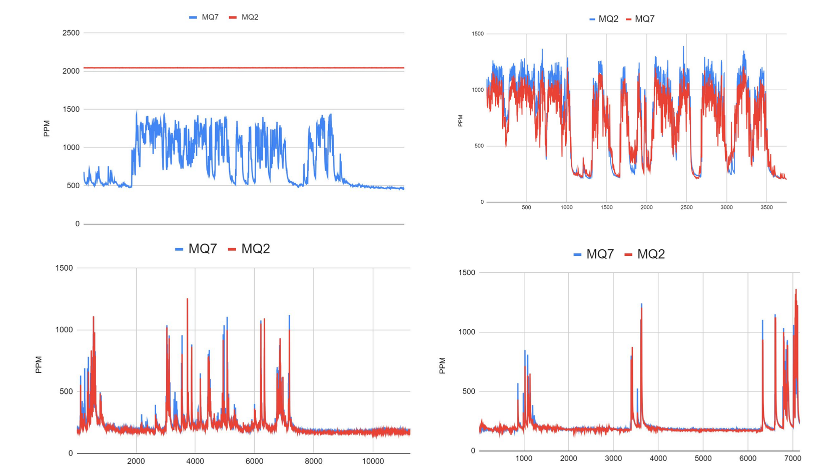
METEC Field Testing Results

Complicated Structure Testing



Data Collection

- SPIRo Field testing was done at Methane Emission Technology Evaluation Center at Colorado State Univ.
- Distance, emission amount, and weather data varies
- Gas sensors calibrated with clean air and calibrated gas
- Dual gas sensor values are collected at 1Mhz by the MyRIO and Labview and passed on to computer for AI processing
- Ran data through machine learning algorithm in real time
- Leak or no leak and severity of the gas leak is decided



- 4 emissions, 7.5 hours + 27000 data points over 3 days
- 77% accuracy on leak detection
- Collected gas sensor data, thermal imaging data
- Significantly more noise than data in simulated testing environment due to weather conditions such as wind
- Cast Iron required higher magnet strength for the magnetic feet

Leak Detection Testing

Pipe Locomotion Techniques

Conclusions & Future Work

- SPIRo, an AI based soft robot with multidimensional locomotion has been successfully designed and implemented for gas leak detection
- Real field data collection and testing results indicate success of real time leak detection with an accuracy of 77% in outdoor environment
- Individually controlled McKibben muscle actuators allow for horizontal, vertical, and lateral steering, magnetic feet makes the climbing of complex pipes possible
- Multimodal data gas sensor and thermal images with ensemble learning achieves high accuracy and redundancy
- Future work: FlowIO to improve operating range, solar panel for power, data augmentation for image preprocessing

Selected References

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