

LeakLink - Design

Adithi Phadke, Rayann Ramoutar, Mahati Manda

Use-Case Requirements

Problem:

Civil and HVAC Engineers need to inspect pressurized ductwork regularly

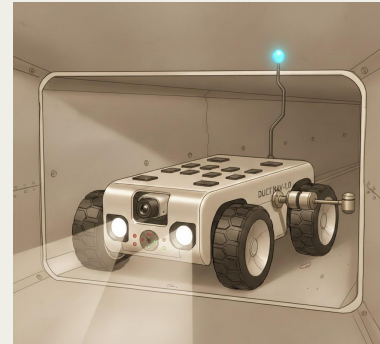
- Manual Inaccessibility
- Inaccurate Diagnostics
- Undetected Degradation



Solution:

We will design a remote-controlled robot that

- Maneuvers the HVAC duct systems
- Detects corrosion and air leaks
- Pinpoints location of defects
- Generalizes across different materials



Quantitative Design Requirements

Must fit within ducts	12" height and weight
Tap spacing must be 10 cm	Corrosion region length is 10 to 20 cm
Runtime at least 30 minutes	Based on length of duct and speed of robot
Tap jitter must be less than 2 ms	IMU motion gating and sensitivity of acoustic data
Sampling rate must be greater than 200 kHz	Represent frequencies lower than 100 kHz without aliasing
Recording window must be greater than 100 ms	Accounts for ring-down time of galvanized sheet metal
19V Power Source	Jetson requires 19V of power
Classification Performance of 85%	Common accuracy rate found in other defect classification models

Solution Approach

How the Robot Works

- Piezoelectric sensor detects acoustic/vibration signals
- Signal passes through preamplifier
- Processed for classification

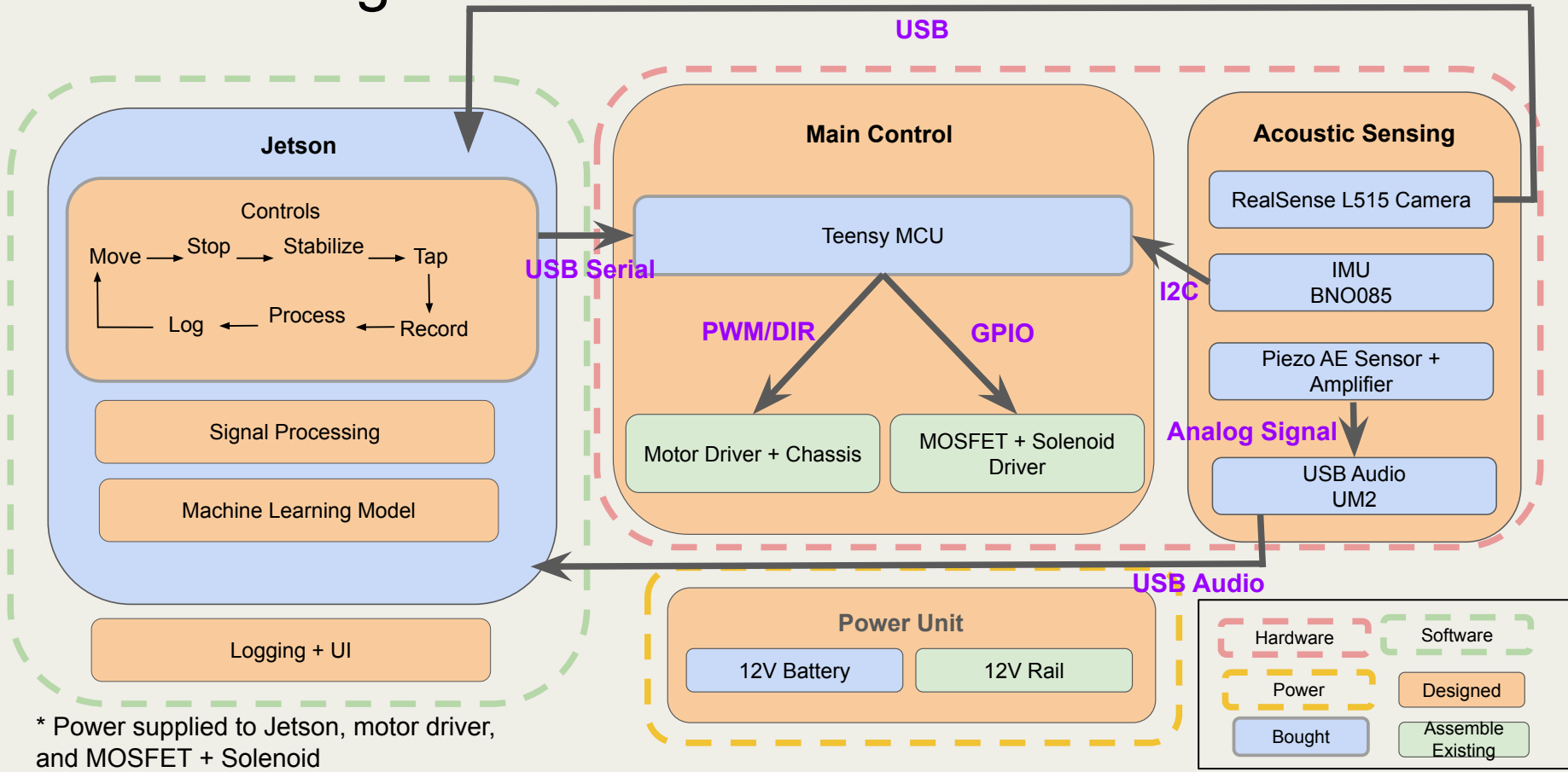


Revised Data Strategy

- We will be building our own supervised dataset
- Acquired metal duct from trade school for this purpose
- AE signals, Classification Labels



Overall Design



Hardware Choices & Implementation



Teensy 4.0 MCU



NVIDIA Jetson Orin Nano



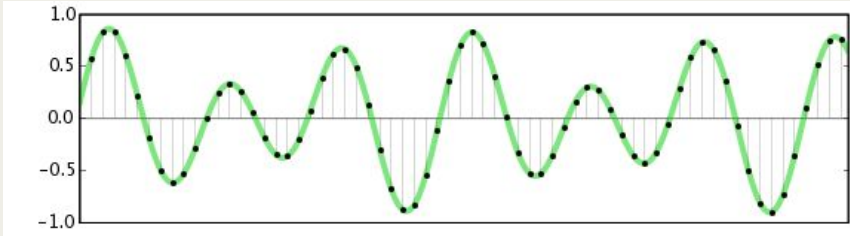
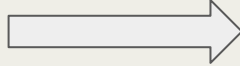
12V LiFePO4 Battery



Piezo AE Sensor

Software - Data Processing

Digital Acoustic
Data



Bias Shift (due to turbulence)



Denoising Process



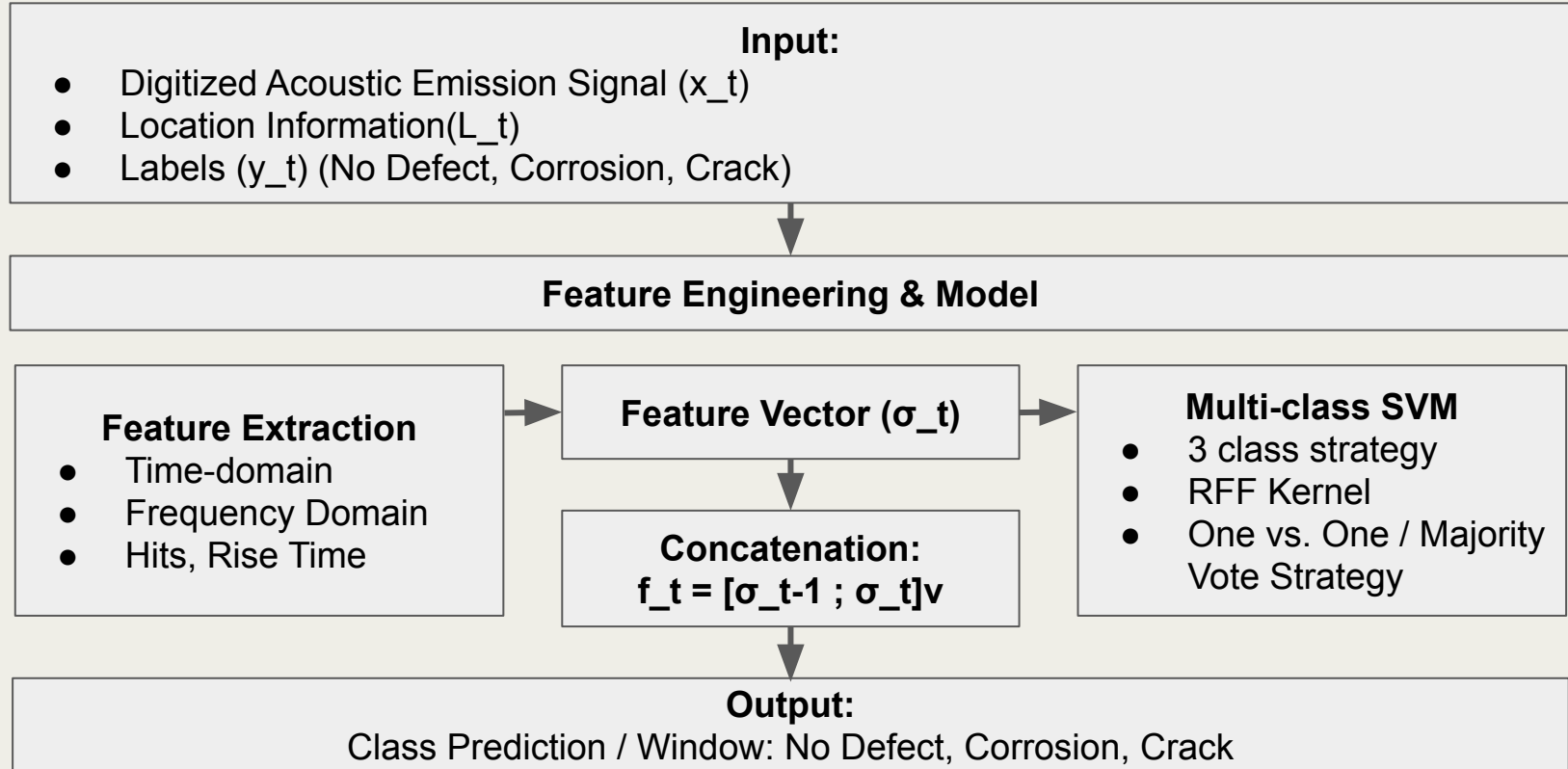
Time Domain: Peak-to-peak, RMS



FFT

Frequency Domain: Angular Frequency, Mean Frequency, Mean Frequency Power, Frequency Window Selection

Software - Classifying Defects



Software Implementation

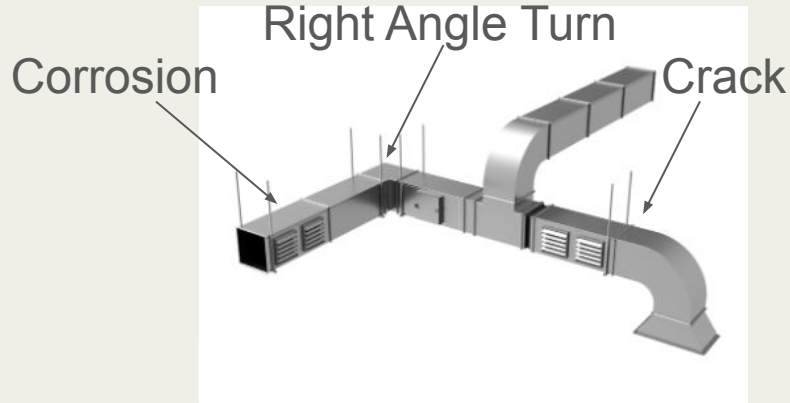
Preprocessing Signals



Classifier ML Model



Testing, Verification, and Metrics



Using two materials: sheet metal duct & fiberglass duct board

Corrosion	Surface Prepping: Sandpaper target area to strip galvanized layer Acid Spray: 5% NaCL and 1% Acetic Acid solution Cycle: Wrap area with damp paper towels to trap moisture in the metal Forced Dry: 1 hour using heat gun to accelerate evaporation
Cracks	Longitudinal Slot: 0.5-5 mm wide with thin saw Seam Holes: 3 mm - 10 mm at duct junctions Partial Notches: 25%-50% of wall thickness using milling bit to imitate thinning wall

Testing, Verification, and Metrics

Precision	Number of times robot was correct in identifying defects	$TP/(TP + FP)$	85%
Recall	Number of defects robot identified	$TP/(TP + FN)$	85%
Dice Score	Similarity between two areas	$2 * \text{overlap area} / \text{total area}$	85%
Position Error	Error between true position & reported position	$e = \hat{p} - p $	>10 cm
Relative Error	Relative error between true & reported position	$rel_e = (\hat{p}_2 - \hat{p}_1) - (p_2 - p_1) $	>10 cm
Turn Accuracy	Error between 90° and true angle turned	$e = 90^\circ - \text{true angle} $	>10°
Turn Reliability	Turn Success Rate	Successful Turns / Total Turns	85%
Sampling Density	Taps per meter	Number of taps / distance	Tap every 10 cm
Signal Clarity	Signal to Noise Ratio	Signal Power / Noise Power	>25 dB

Risks & Mitigation

Risks	Mitigation
System stops working	Watchdog + Protocol to bring robot out of HVAC
Noise in Ducts Interfering with Signal	Use a preamplifier with our AE sensor to remove noise and amplify the signal
Precision not high enough	Make sure to have an increased sampling density to more than one tap every 10cm
False Positive Defect Detected, Not Present	• Unnecessary maintenance visits • Increased service costs
False Negative Defect Not Detected, Present	• Equipment damage • Expensive long-term repairs

False negatives are more dangerous than false positives as undetected faults can escalate.

Schedule

[illegible]