Predictive Acoustic Signature Analysis for Mechanical Health Monitoring

Applying MASINT-Inspired Techniques to Detect Early Mechanical Degradation

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Outline

- Executive Summary
- What is MASINT?
- Purpose & Objective
- The Approach
- Hardware Design
- Software Tools & Development
- Testing Phase
- Results Analysis
- Future Development

ACOUSTIC SENSOR PROJECT OVERVIEW

Predictive Acoustic Signature Analysis for Mechanical Health Monitoring

Applying MASINT-Inspired Techniques to Detect Early Mechanical Degradation

PROJECT OBJECTIVE

Can we use Acoustic Sensors to Detect Degradation of a system earlier than traditional methods?

Hypothesis:

Mechanical systems produce unique acoustic fingerprints. As components age, wear, loosen, or degrade, microscopic physical changes alter their acoustic signatures before visible or functional failure.

WHAT I DID – END TO END

1. HARDWARE DEVELOPMENT

- Selected & tested components
- Arduino Nano (initial prototype)
- Raspberry Pi Pico (improved prototype)
- MAX4466 Electret Microphone
- MicroSD Storage & OLED Display
- Designed & built custom enclosure

2. TESTING & DATA COLLECTION

- Built controlled test environment
- Tested Fans, Motors, Bearings
- Simulated degradation: imbalance, loose parts, tape on fan blade, worn bearings
- Collected 10–15 recordings per condition (~30 sec each)
- Standardized mic placement (~10 inches)

3. SIGNAL PROCESSING & FEATURE EXTRACTION

- Converted time-domain audio to frequency domain
- Generated FFTs
- Created Spectrograms
- Extracted key features:
  - Frequency Peaks
  - Amplitude Trends
  - Harmonics
  - Noise Patterns
  - Spectral Signatures

4. ANALYSIS & DETECTION DEVELOPMENT

- Compared degraded signatures to healthy baselines
- Identified deviations & anomalies
- Built detection logic for early degradation identification
- Explored ML concepts for classification

5. VALIDATION

- Validated through multiple test scenarios
- Evaluated effects of:
  - Noise
  - Distance
  - Orientation
  - Device variability
- Confirmed detection of subtle degradation before failure

FUTURE OBJECTIVES

FULL AUTONOMOUS AI DETECTION

- Develop fully autonomous system that can:
  - ✓ Continuously monitor systems
  - ✓ Automatically detect degradation
  - ✓ Classify fault type & severity
  - ✓ Predict remaining useful life
  - ✓ Alert users in real-time
- Edge AI implementation for real-world deployment
- Scalable across multiple systems and industries

HARDWARE EVOLUTION

INITIAL PROTOTYPE (Arduino Nano)

- Rapid learning platform
- Validated basic acoustic collection
- Identified system limitations

IMPROVED PROTOTYPE (Raspberry Pi Pico)

- Faster processing
- More memory
- Better ADC resolution
- Supports future expansion & real-time analysis

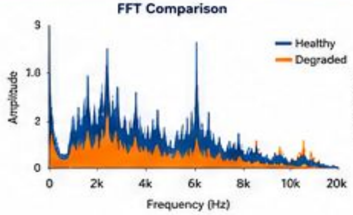
KEY SENSOR (MAX4466)

- Captures 20 Hz – 20 kHz
- Adjustable gain
- Detects imbalance, wear, friction, vibration

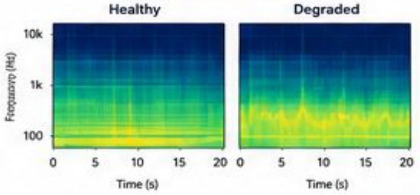
Custom Enclosure Designed for Durability, Portability, & Real-World Use

DATA & ANALYSIS RESULTS

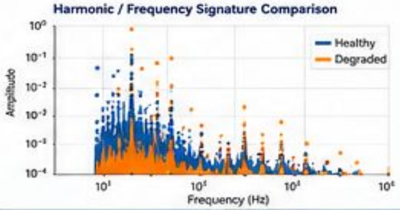
FFT Comparison



Spectrogram Comparison



Harmonic / Frequency Signature Comparison



WHAT WE FOUND

- Degraded systems show clear changes in frequency peaks, harmonics, and noise patterns
- Subtle degradation is detectable before audible/functional failure
- Acoustic signatures are consistent and repeatable across trials

TEST SYSTEMS & CONDITIONS

Systems Tested

- Fans
- Motors
- Bearings
- (Future) HVAC Systems
- (Future) Water Pumps
- (Future) Drones

Degradation Conditions

- Imbalance
- Loose/Broken Parts
- Worn Bearings
- Degraded Coils
- Obstruction / Friction

TOOLS & SOFTWARE

Python	NumPy, SciPy, Librosa, Matplotlib, Scikit-learn
MATLAB	Signal Processing & Data Analysis
Arduino IDE	Sensor Control & Data Logging
Google Colab	Cloud Computing & Data Processing
Spectrum Lab	Advanced Signal Analysis
CAD Tools	Onshape / SolidWorks (Enclosure Design) & 3D Printing

KEY TAKEAWAYS

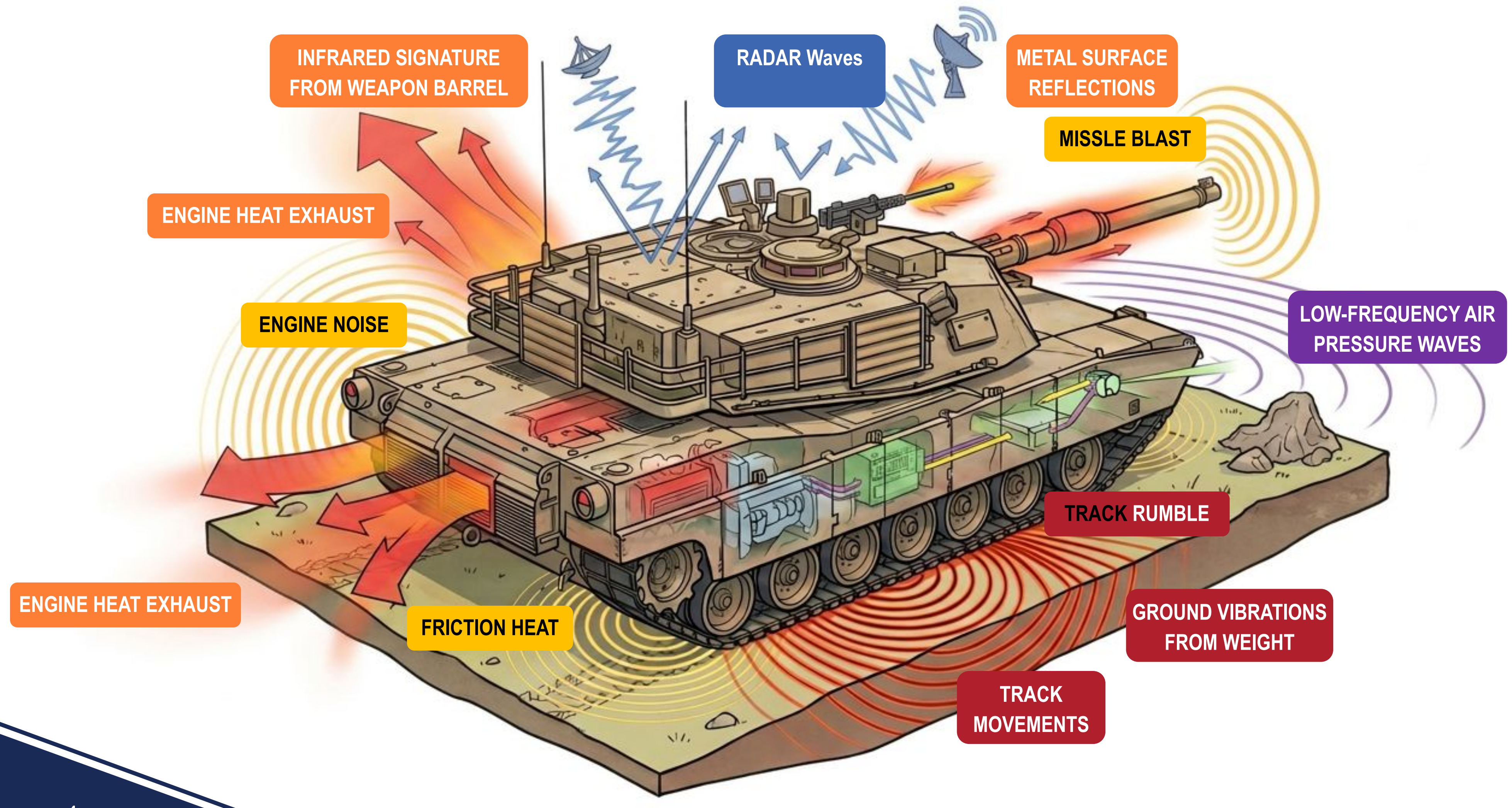
- Acoustic sensing is an effective early indicator of mechanical degradation.
- MASINT principles provide a strong framework for signature-based analysis.
- Our prototype successfully detects subtle changes before traditional methods can.
- This technology has wide applications across many industries.

IMPACT & APPLICATIONS

Aerospace	Engine health monitoring
Industrial	Predictive maintenance
Energy	Turbines & generators
Utilities	Pumps & HVAC systems
Defense	UAS & critical systems

This project demonstrates that acoustic signatures can reveal the hidden story of mechanical health—before failure occurs. ***The future: Fully Autonomous AI Detection.***

MASINT Stands for Measurement & Signature Intelligence

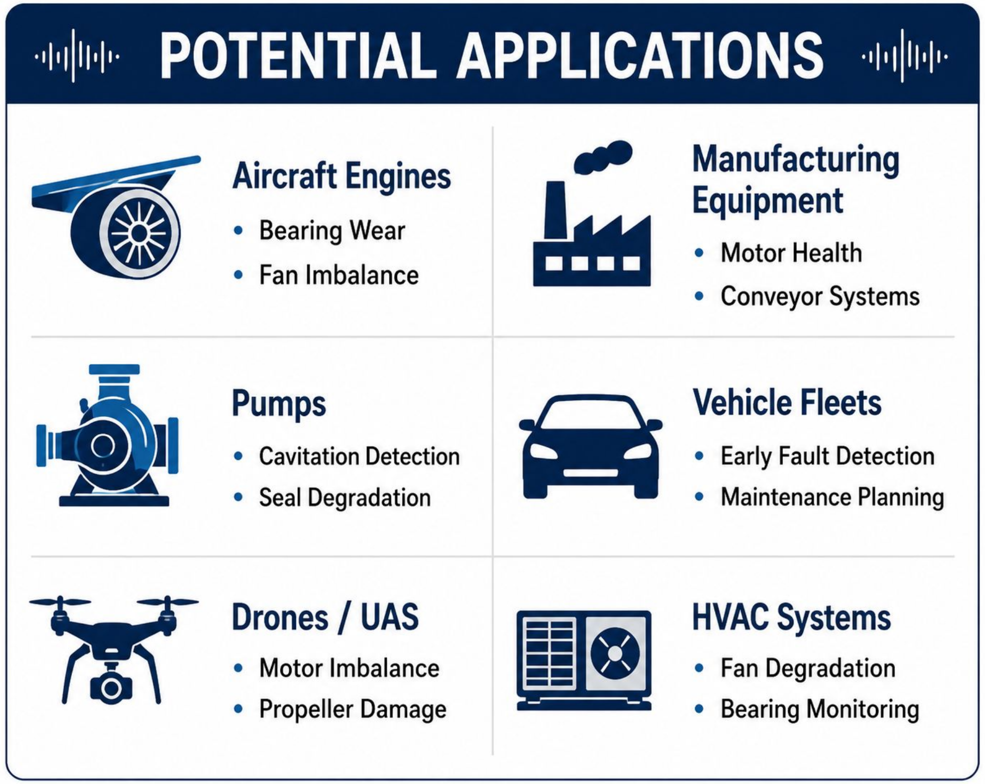


MASINT is collecting data of what you can't see directly, such as plumes and sound.

Purpose & Objective

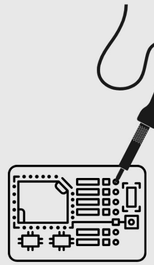
Predictive Acoustic Signature Intelligence using MASINT techniques for System Health Monitoring

Mechanical systems produce unique acoustic fingerprints. As components age, wear, loosen, or degrade, microscopic physical changes alter their acoustic signatures before visible or functional failure which we are able to identify.



The Plan - From Start to Finish

Design and Development of Hardware Prototype



Determined testing setup, what hardware to utilize, and fitting it into a case

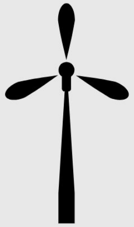
Initial Acoustic Data Collection

Collected baseline data from a quiet room and basic fan at varying distances

Signal Processing and Feature Extraction

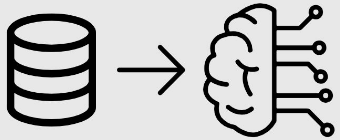
Utilized software to create and evaluate spectrograms and FFT data

Expanded Data Pool with large UAV Propellers



Retrieved data from SCC's UAS department for more meaningful results

Database Creation and Beginning of Machine Learning



Combined samples into a database our ML model can train on

Approach

Mechanical System

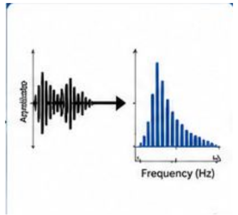
Fans & motors to begin with; Other mechanic systems in the future

Operated under healthy and degraded conditions

Acoustic Sensor

Custom-built microphone captures acoustic signatures

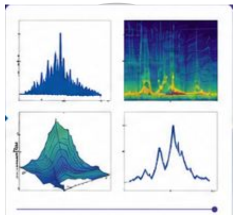
Consistent testing environment



Signal Processing

Convert time-domain audio to frequency domain

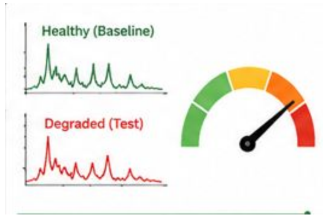
Generate FFTs for analysis



Feature Extraction

Frequency Peaks   *Amplitude Trends*   *Harmonics*

Noise Patterns   *Spectrograms*



Signature Comparison & Health Assessment

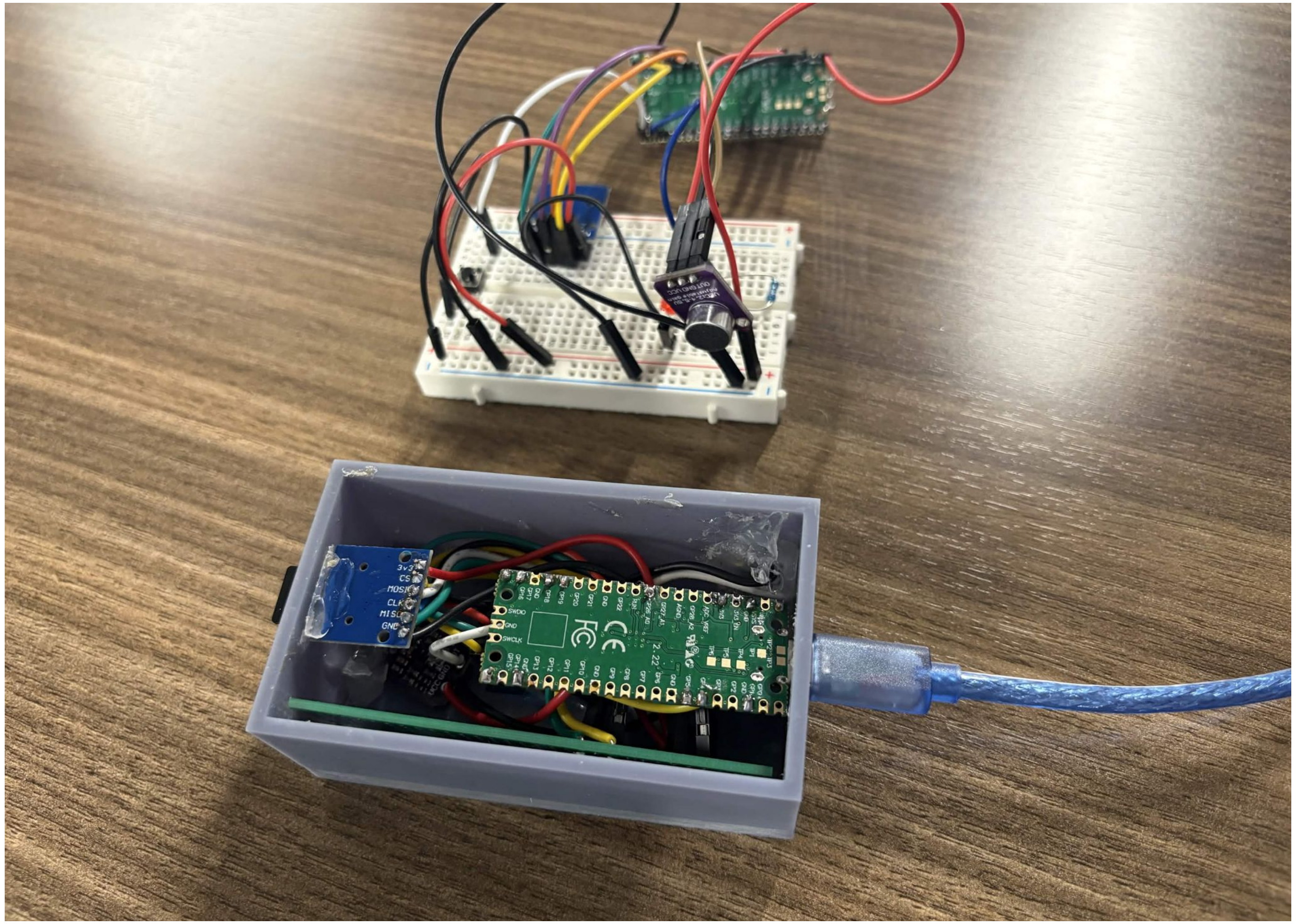
Compare extracted features against healthy baseline recordings

Easily identify deviations and anomalies & determine system health condition

Hardware Design

From the beginning, we knew building our Acoustic Sensor from scratch would personalize the experience.

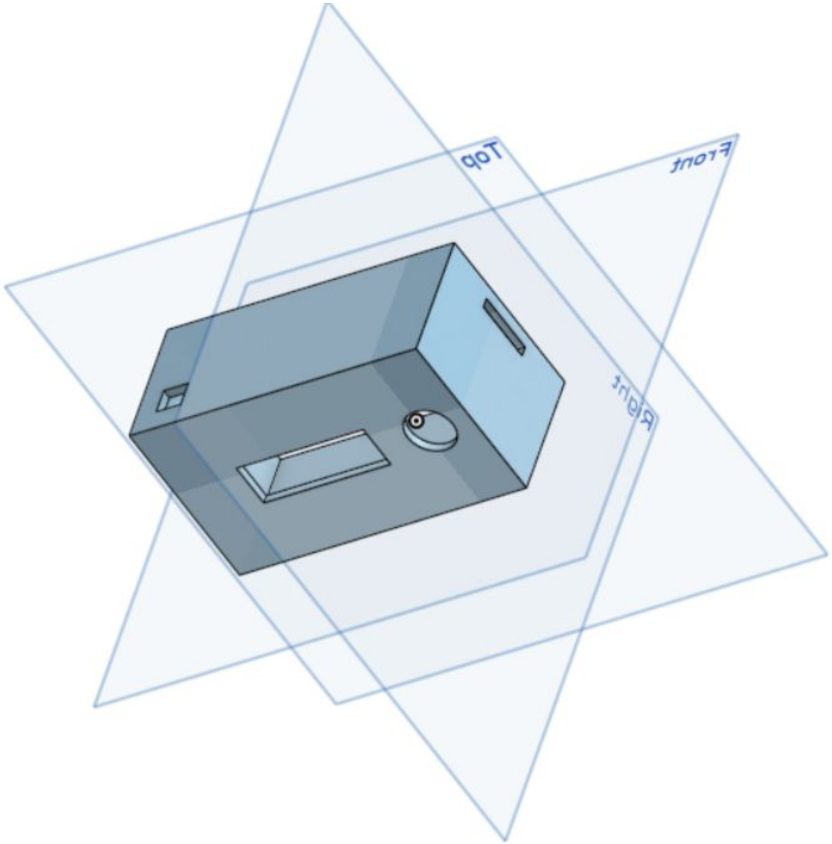
We started by using the motherboard & sensor to ensure easy cable routing, proper clearance ,allowing a pre-test to ensure everything works.



Designing the Case

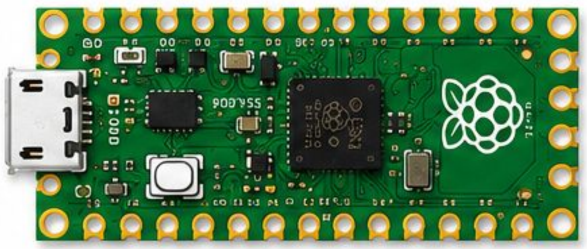
A rugged, portable enclosure is an important step toward deploying acoustic signature sensing outside the laboratory.

- Designed a custom protective enclosure for the prototype, improving durability by protecting electronic components from damage.
- Increased portability by integrating components into a compact, self-contained design.
- Created a foundation for future field testing and design enhancements.



Sensor & Board Choice

RASPBERRY PI PICO (RP2040)



FEATURE	SPECIFICATION
CPU	RP2040
Architecture	32-bit ARM Cortex-M0+
Clock Speed	133 MHz
Cores	2
Flash Memory	2 MB
SRAM	264 KB
Digital I/O Pins	26
Analog Inputs	3 (ADC channels exposed)
ADC Resolution	12-bit
USB	Micro-USB
Typical Cost	~$5

High Performance
Dual-core processor at 133 MHz

Low Power
Efficient architecture for battery-powered applications

Developer Friendly
MicroPython, C/C++ and CircuitPython support

Compact & Versatile
Small form factor with rich I/O capabilities

Affordable
Highly capable at a low cost

MAX4466 ELECTRET MICROPHONE MODULE

FEATURE	SPECIFICATION
Power Supply	3.3 V
Frequency Range	20 Hz – 20 kHz
Audio Gain Range	25x – 125x
Gain Setting Used	Default values (Factory Setting)

IDEAL FOR DETECTING:

- Fan blade imbalance
- Motor noise
- Bearing wear
- Mechanical vibration signatures

High Sensitivity
Captures a wide range of acoustic details

Adjustable Gain
On-board potentiometer for flexible sensitivity control

Wide Frequency Response
20 Hz – 20 kHz for clear audio capture

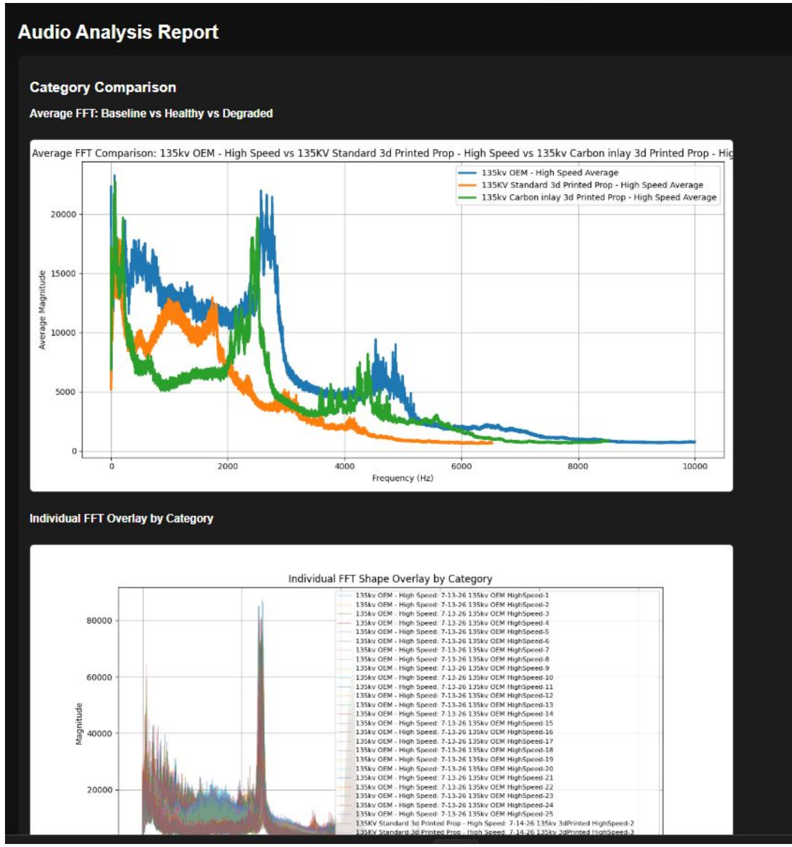
Easy to Use
Simple 3-pin interface: OUT, GND, VCC

Affordable
High performance at a low cost

Software Python / Scripts

Custom Python scripts transformed raw acoustic readings into data products used for comparison of healthy & degraded systems

```python

GroupOne = "135kv OEM - High Speed"
GroupTwo = "135KV Standard 3d Printed Prop - High Speed"
GroupThree = "135kv Carbon inlay 3d Printed Prop - High Speed"


# ========================
# SETTINGS
# ========================

SAMPLE_RATE = 20000
RAW_DTYPE = np.uint8
OUTPUT_FOLDER = "audio_report_output"


# ========================
# AUDIO FUNCTIONS
# ========================

def clean_name(path):
    return os.path.splitext(os.path.basename(path))[0]


def load_raw_audio(path):
    audio = np.fromfile(path, dtype=RAW_DTYPE)

    if RAW_DTYPE == np.uint8:
        audio = audio.astype(np.int16) - 128

    return audio

```



Code to Results

Supporting Software

Audacity

- Open source audio editor and recorder
- Used for listening to recordings, and manual Inspection
- Helpful for trimming, noise reduction, and quick verification

Arduino IDE

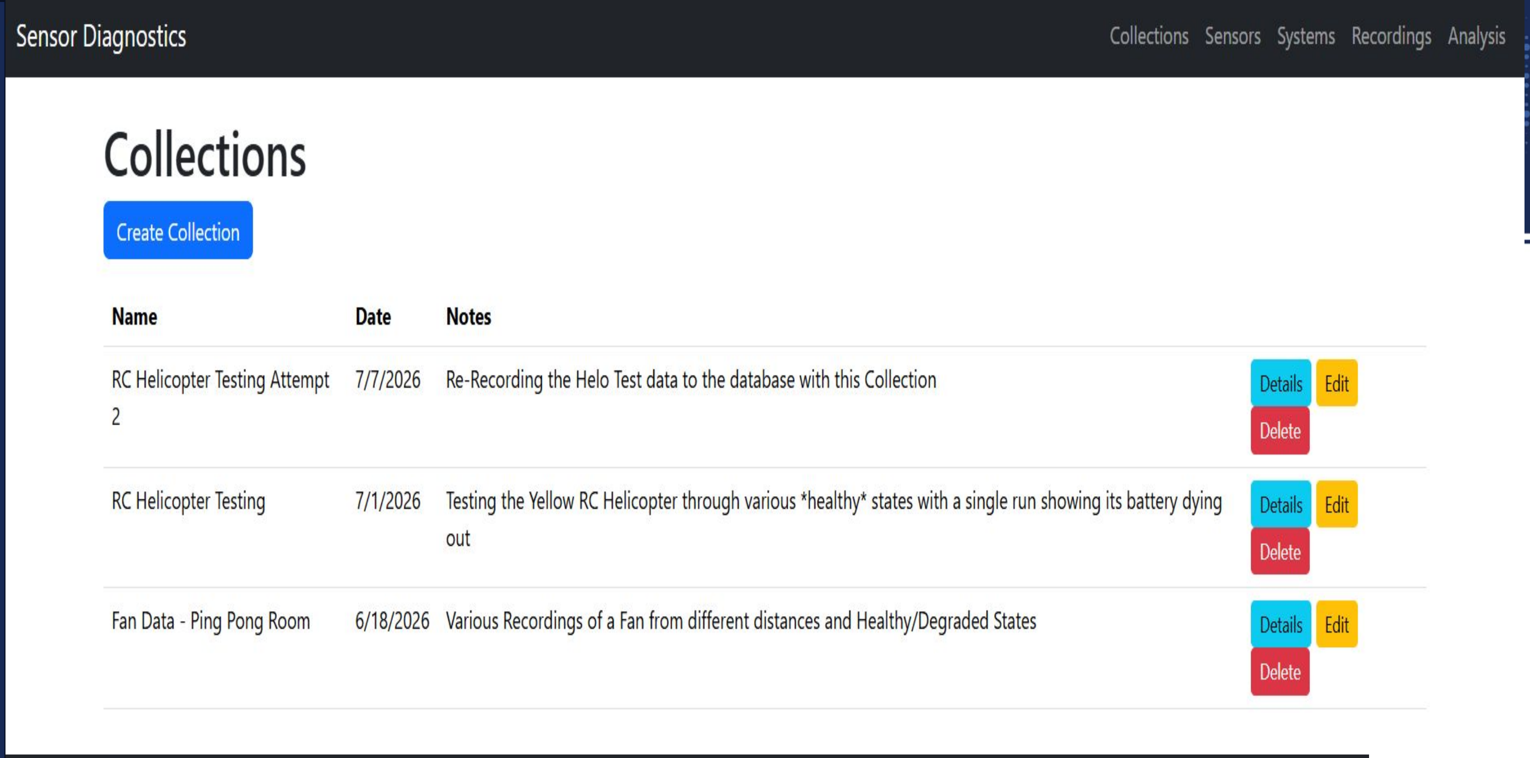
- Allows for the programming of the Raspberry Pico
- Gives a Serial Port Interface with the Pico & Arduino Nano

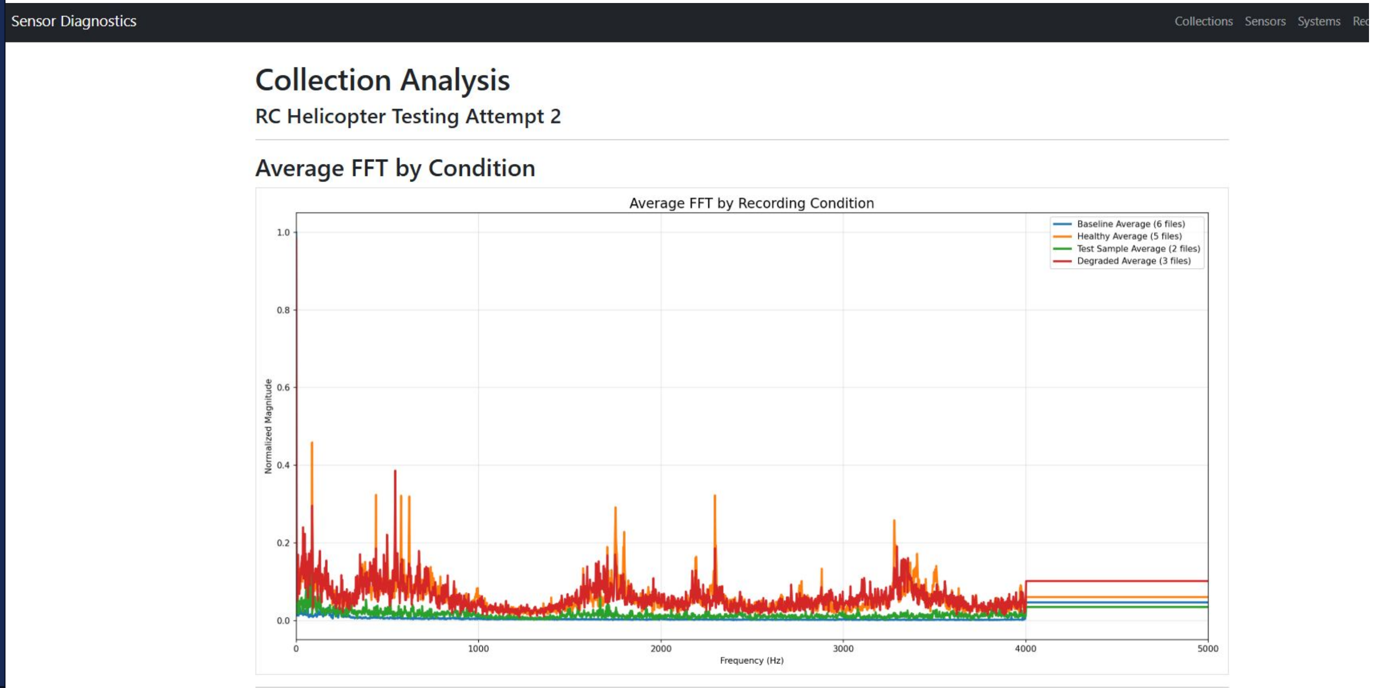
UNCLASSIFIED

Database Dashboard

Current display of the Dashboard

- Allows us to import and export our data
- Allows the integration of Machine Learning to semi-automatically detect degradation





Comprehensive Testing with Sinclair

Through Sinclair, we were able to do several tests, changing out these variables

135 kV & 100 kV motors

Original Equipment Manufacturing (OEM) and two types of 3D-printed propellers

And lastly - changing the RPM of the props through a low & high static speed test, and a final “variable speed” test that simulates in flight

National UAS
Training and Certification Center

US MASINT FOUNDATION
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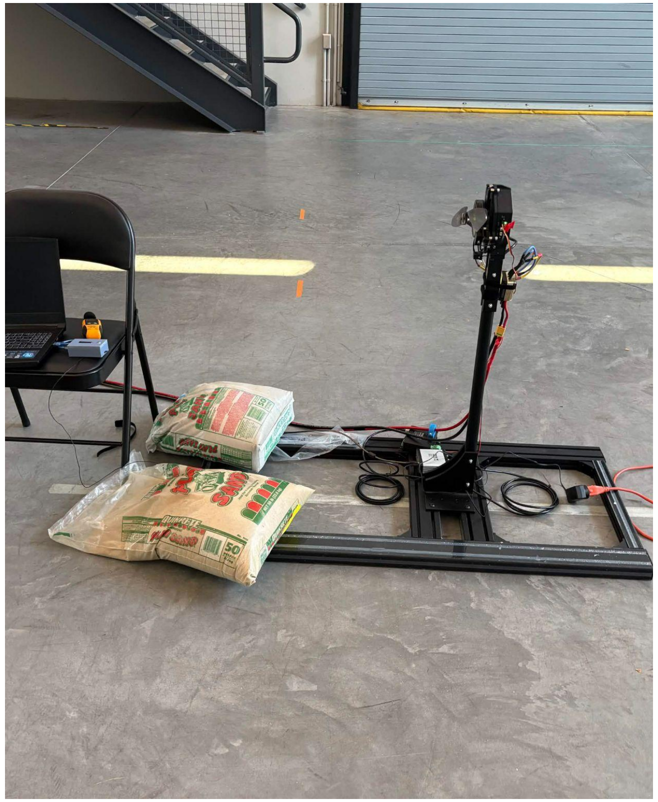
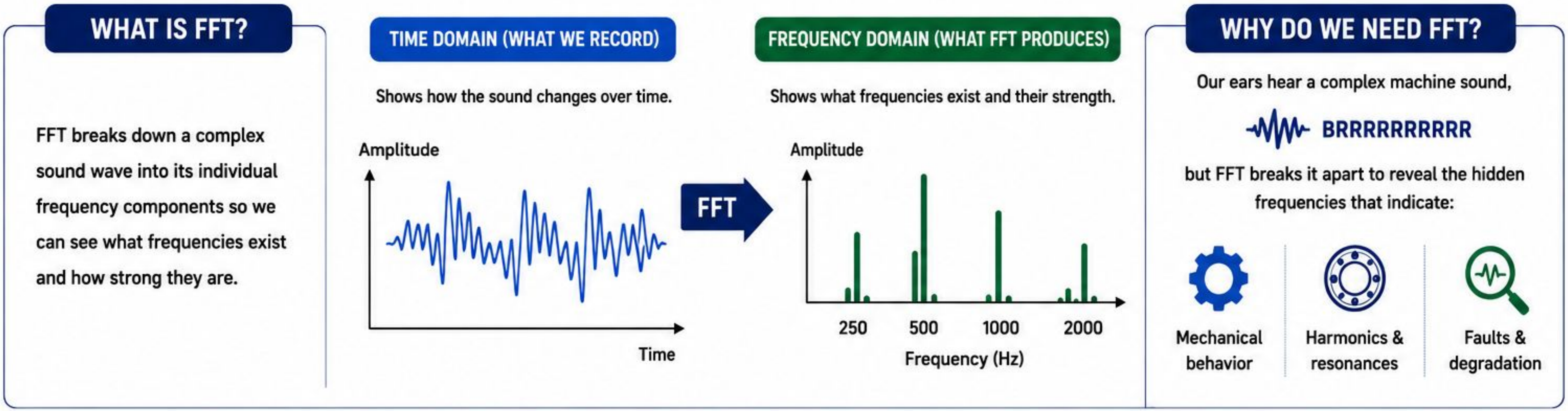
UAS Test Stand & Setup



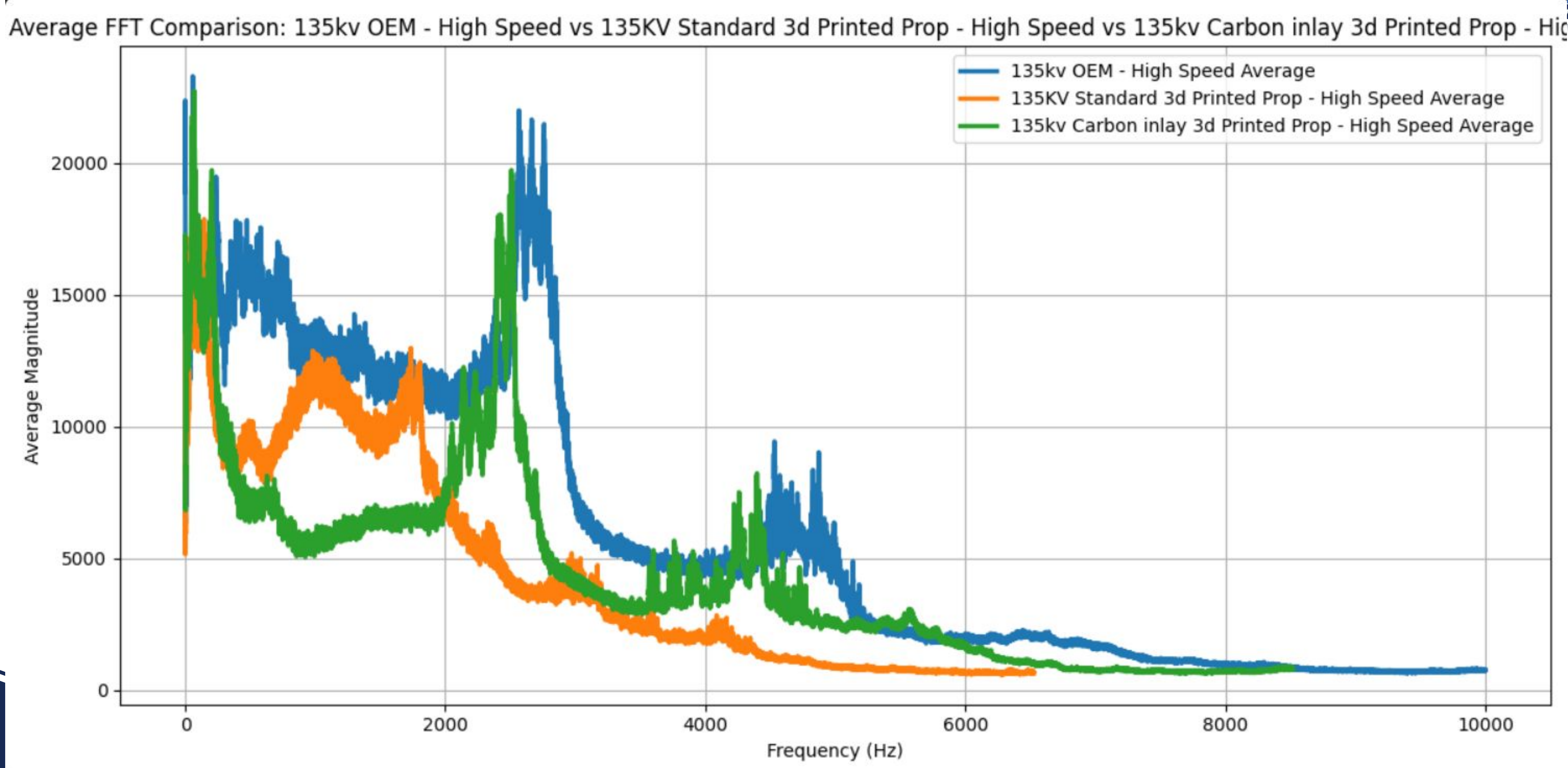
Side View

What is Fast Fourier Transform?

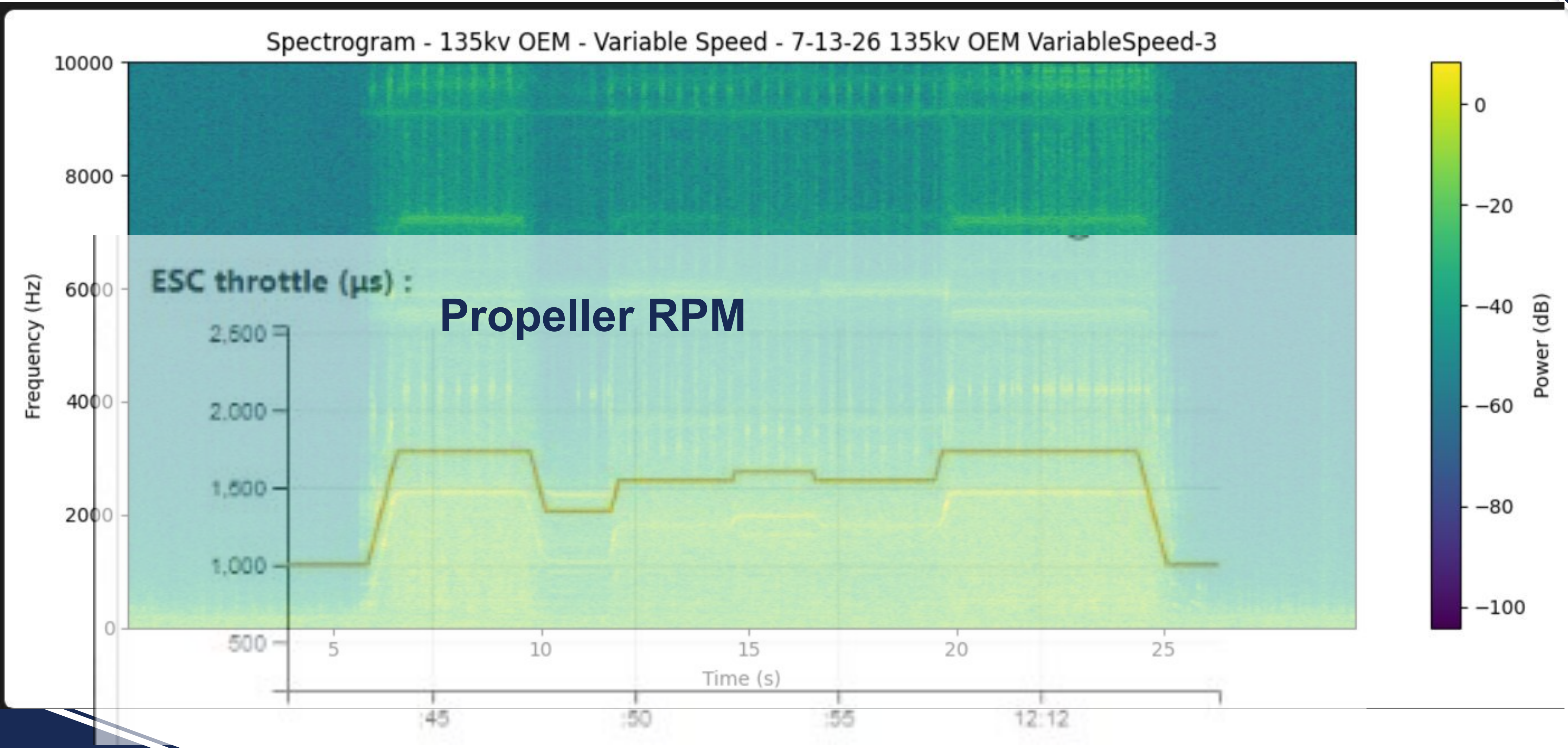
FFT transforms acoustic measurements into quantitative signatures that can be compared to identify anomalies and assess system health.



Different Props, Different Results



Acoustic Spectrogram

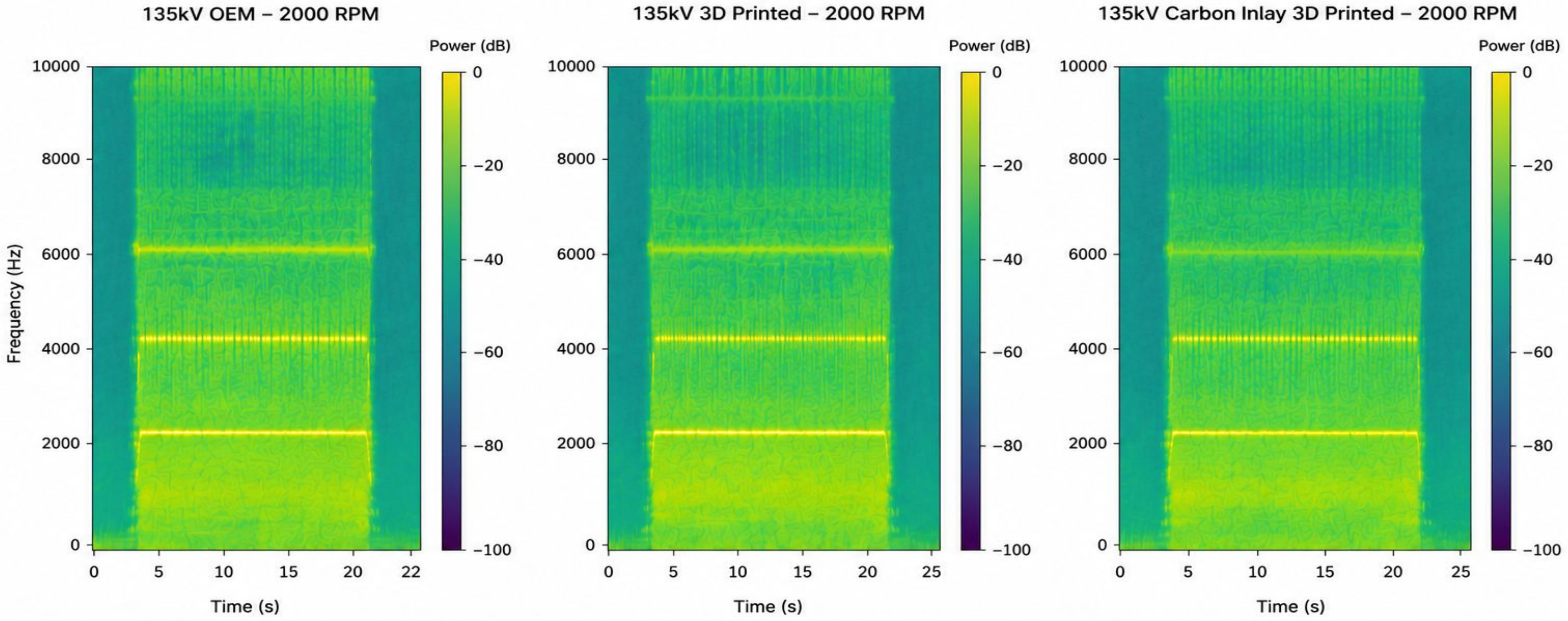


Early Correlations

1. OEM PROP (STANDARD)

2. STANDARD 3D PRINTED PROP

3. CARBON INLAY 3D PRINTED PROP



Motor: 135kV

Power: High Speed (2000 RPM)

Propeller Size: ~24 Inches (Diameter)

Environment: Indoor Lab

Future of the Project

Refined Dashboard

A faster, smoother experience with data collections & analyzation through the dashboard

More Sensors Implemented

Adding more Acoustic and Other type of Sensors (such as Hyperspectral) will allow for better correlation of data, providing faster detection of signs of degradation

Automatic AI Detection

Having a AI Agent that has access to real-time sensor data would allow for immediate detection

Thank you!

Connect with us!

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Nick

Riley

Rachel

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