Universität St.Gallen

# Hearing Problems: Exploring Acoustic-sensing for Predictive Maintenance


Prof. Dr. Bruno Rodrigues



*With many thanks addressed to our MCS students:*
*Valentin Huber, Stefan Krummenacher, Tibor Haller, and Jonas Länzlinger*

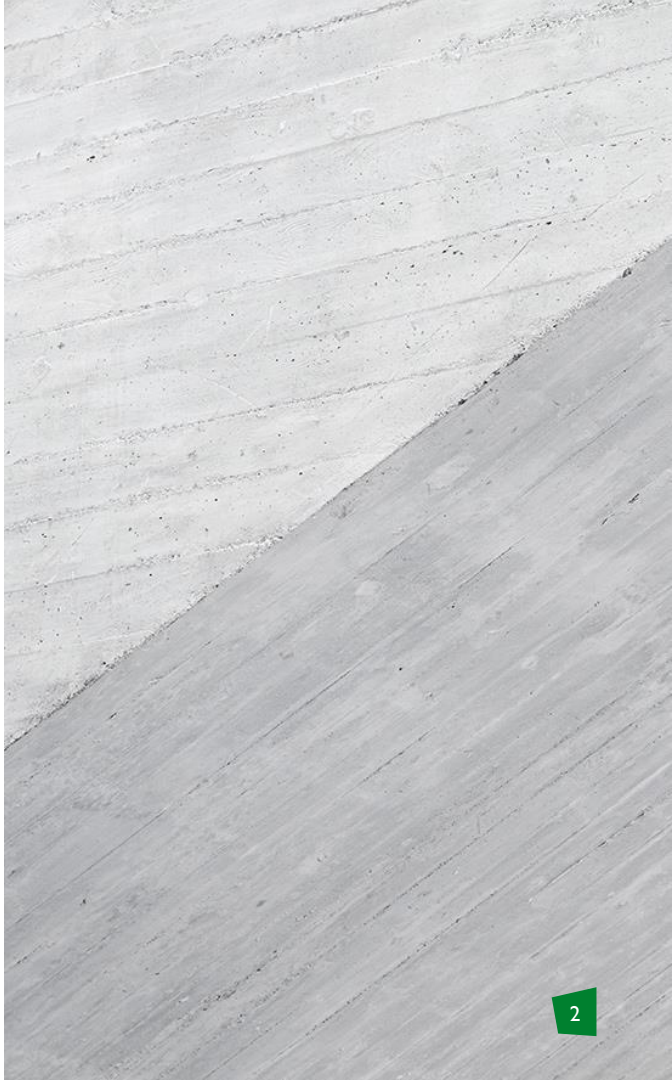


Institut für Computer Science in Vorarlberg (ICV-HSG)


From insight to impact

# Agenda

1. Modern Manufacturing and Machine Maintenance
2. Acoustic Sensing
3. Pumped Storage Hydropower Acoustic-sensing
4. Summary and Takeaways



# 1. Introduction

## Modern Manufacturing and Machine Maintenance

# Evolution of Manufacturing

INDUSTRY 4.0

**Integration of technologies**

- Internet-of-Things (IoT), Artificial Intelligence (AI), Robotics

**Interconnected systems**

- Human-to-machine (H2M), machine-to-machine (M2M)

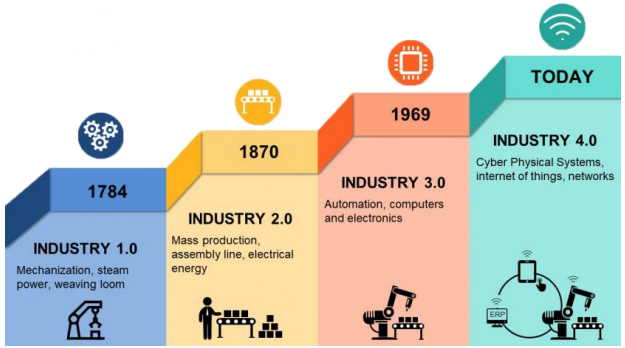
**Data-driven insights**

- Real-time data sharing and decision making

**Automation and customization**

- Robotic arms, transport beds, specific machines

*Machines have always been the backbone of industrial operations… however, they also fail*




Textile factory, 1784

Ford manufacturing line, 1913

Food packaging, 2018

Car manufacturing line, 2023

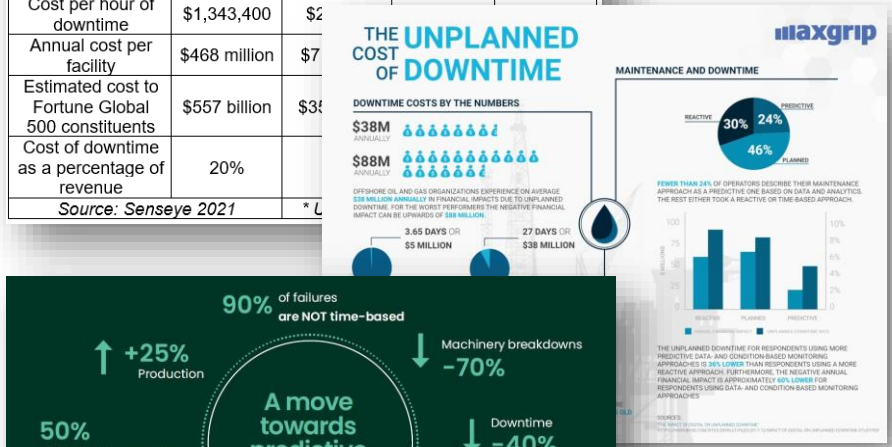
# High Cost of Failures

Machines can fail for **multiple reasons**
- Wear and tear: natural degradation
- Manufacturing defects: faults during the production
- Operational stress: overload or excessive use
- Incorrect operation: mishandling in usage

Downtimes are **costly**, but **very costly** when unplanned
- Significant financial impact: as indicated by multiple surveys
- Disrupting operations: halt in manufacturing line with multiple side-effects
- Planned maintenance is key: scheduled maintenance reduces significantly failures and costs
  - And that is not a novelty!

*How, in our current "Industry 4.0" era, we can **improve** existing predictive maintenance processes?*

| Cost of Downtime | Automotive | FMCG/CPG | Heavy Industry | Oil & Gas |
|---|---|---|---|---|
| Unplanned downtime hours per facility each month | 29 | 25 | 23 | 32 |
| Cost per hour of downtime | $1,343,400 | $2 | | |
| Annual cost per facility | $468 million | $7 | | |
| Estimated cost to Fortune Global 500 constituents | $557 billion | $3 | | |
| Cost of downtime as a percentage of revenue | 20% | | | |
| *Source: Senseye 2021* | | * U | | |



# Scheduled vs Predictive Maintenance

## Scheduled maintenance

- Regardless whether it is the manufacturing or automotive industry, railway companies, or power plants, manual inspection is a burden

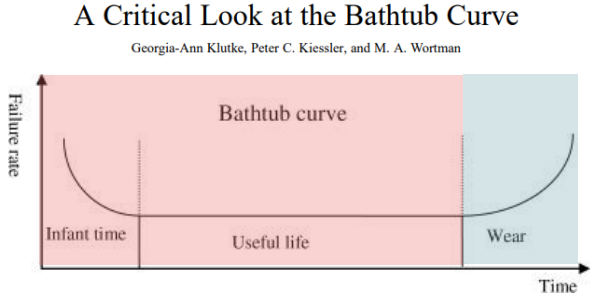
## Condition-based Monitoring (CbM)

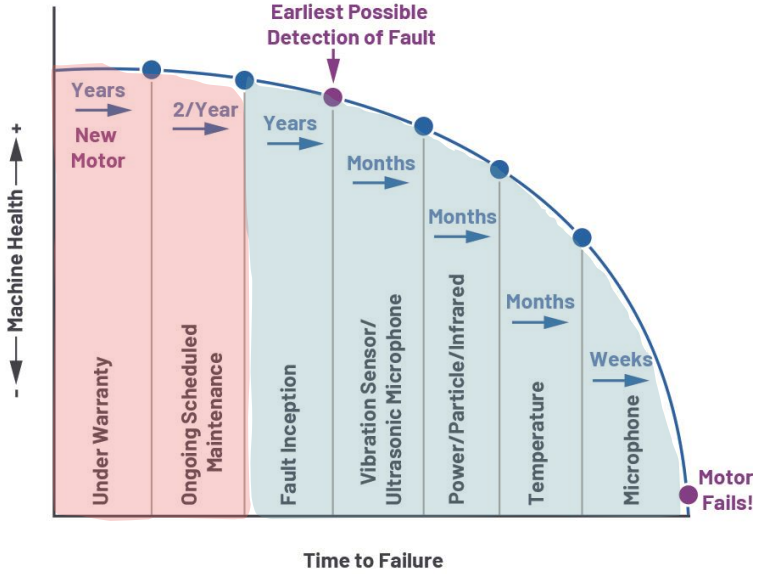
- Monitoring machines or assets using sensors to measure current state of health

## Predictive maintenance (PdM)

- Combination of techniques, including CbM, and ML and Data Analytics to detect patterns and predict anomalies (e.g., MTTD, MTTR, MTBF)

*At its core, predictive maintenance is an "Industry 4.0" activity by leveraging sensor data and analytics to optimize costs and maximize machine uptime*




Source: https://sensemore.io/what-is-condition-monitoring/



*MTT: Mean Time [to Detect, to Repair, Between Failures]

# Predictive Maintenance Classifications

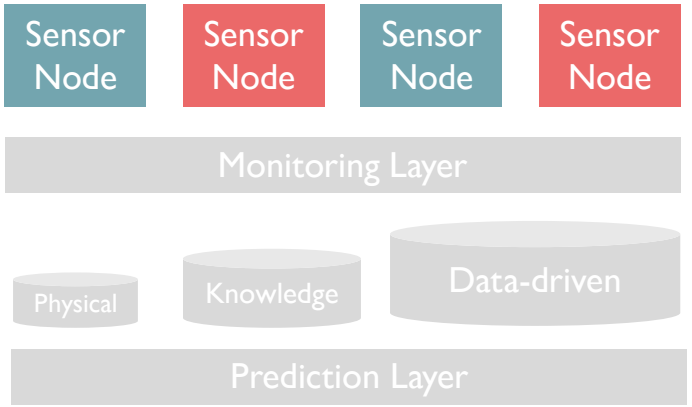
## Approaches

Another essential content related PdM regards the three classifications of the approach used for prediction(Deutsch and He, 2018, Wang et al., 2018, Wu et al., 2017c):

- **Physical model-based**: has as its main feature mathematical modeling with reflexes in the condition of a component, needing the precision of the condition and measurement of failure, and statistical methods to limit these indices(Wu et al., 2017c);
- **Knowledge-based**: approaches that reduce the complexity of a physical model, for this reason, is often used as a hybrid strategy, for example, expert systems or fuzzy logic(Ayad et al., 2018, Wu et al., 2016);
- **Data-driven**: models most found in the current evolution of PdM solutions are statistics-based, pattern recognition, or artificial intelligence (AI) and models based on machine learning algorithms.

Zonta, Tiago, Cristiano André Da Costa, Rodrigo da Rosa Righi, Miromar Jose de Lima, Eduardo Silveira da Trindade, and Guann Pyng Li. "Predictive Maintenance in the Industry 4.0: A Systematic Literature Review." *Computers & Industrial Engineering* 150 (2020): 106889.

*PdM may not always rely **learning-based** approaches, it can also involve **physical** models (e.g., stress, wear) or **knowledge** (e.g., threshold rules or statistical analysis).*




## Sensors

*VIBRATION: Rotating machines (motors, pumps, bearings)*
*TEMPERATURE: Heating-generating equipment (typically also rotating)*
*PRESSURE: Hydraulic systems and pneumatic equipment*
*ACOUSTIC: Can detect subtle changes in machine sounds (often not human-perceived).*
*Among these sensors, acoustic sensing is crucial for identifying anomalies early and accurately.*

# 2. Hearing Anomalies

## Acoustic Sensing

# Acoustic Sensing Principles

## Definition

A method of capturing and analyzing sound waves (vibrations in air or other mediums) emitted by machinery or processes.

## Principles

- **Frequency analysis**: different types of failures, different/unique sound patterns that can be verified using a **Fourier Transform**

- **Sound emission and wave propagation**: understand sound signatures during normal (and/or faulty operations)

## Modeling considerations

Environment plays a significant role

- Multipath fading
- Signal reflections, collisions
- **Positioning of microphones is key**

Sound events have diverse acoustic characteristics

- Short, transient-like sounds, longer duration and harmonic
- **Filter unwanted noises**

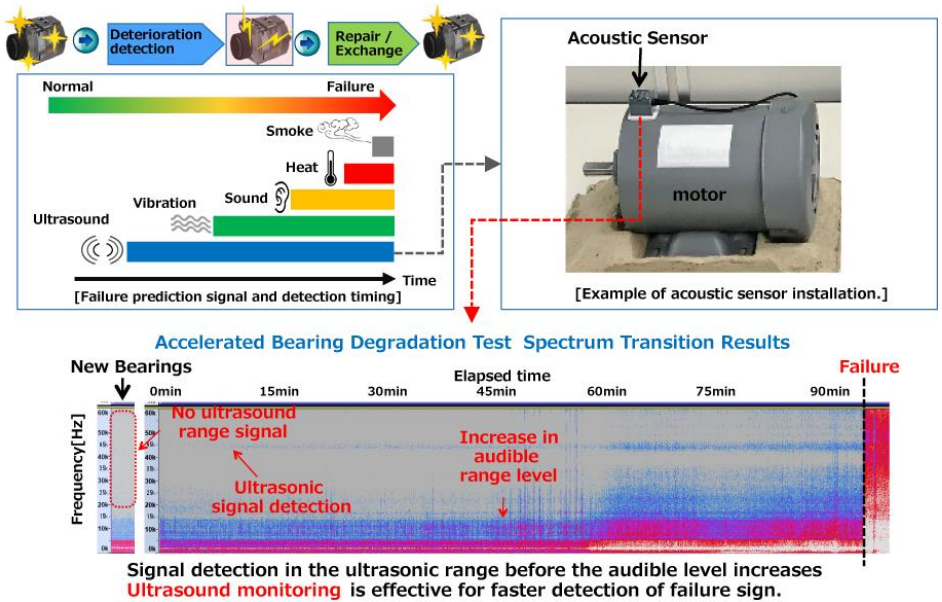
Difficult to profile noise characteristics in a specific model

- Requires lots of data and good analysis: relatively high-cost benefit in contrast to other approaches (e.g., vibration sensors)



Mesaros, Annamaria, Toni Heittola, Tuomas Virtanen, and Mark D. Plumbley. "Sound Event Detection: A Tutorial." *IEEE Signal Processing Magazine* 38, no. 5 (2021): 67-83.

# Example – Rotating Equipment




*Rotating equipment used in factory production equipment has the risk of sudden production line stoppage due to* ***failure caused by bearing wear or damage****, so it is managed by regular maintenance and parts replacement depending on the usage time in general. In preventive maintenance,* ***even usable parts are maintained and replaced****, which results in wasted worker resources and parts replacement costs.*

*https://www.nisshinbo-microdevices.co.jp/*

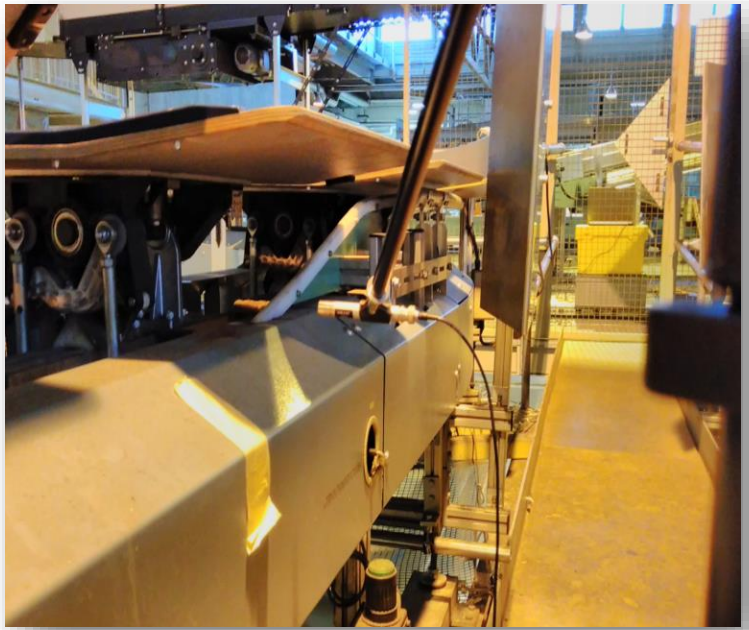
# Boston Dynamics - Improving Energy Efficiency with Robotic Acoustic Inspection



Acoustic-imaging

https://bostondynamics.com/webinars/improving-energy-efficiency-with-robotic-acoustic-inspection/

# Example - Logistics



*"…In a pilot project at the Swiss Post, we were able to successfully demonstrate the benefits of an acoustic solution for monitoring tilt tray sorting systems. Thanks to a single mounted sensor and our Deep Learning-based AI solution, we managed to assign* ***a unique acoustic fingerprint to each of the approximately 900 trolleys*** *in the facility, despite the numerous background noises in the sorting center.* ***Changes in this fingerprint over time are a clear indication of damage****, reducing costly service interruptions and extensive maintenance…"*

***LeanBI:*** https://leanbi.ch/en/solutions/

# 3. Hands-on

## Pumped Storage Hydropower Acoustic-sensing

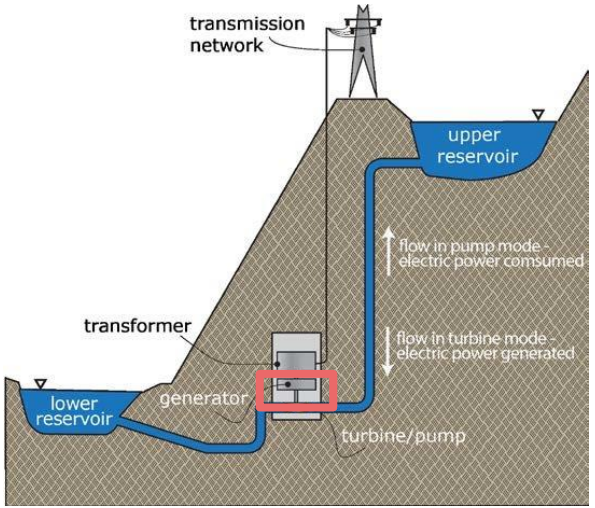
# The Context

## Scenario

- The operation of hydroelectric power plants requires precise monitoring and preventive maintenance
- Predictive maintenance needs to be extremely accurate since downtime costs have **significant impacts**

## Problem/Challenges

- Loud noises when operation changes from **generator** to **pump** mode
- Many reverberations and different machines operating simultaneously
- Imagine you feel your entire body vibrating when you are next to the machine



# “Hearing” Problems

## Opportunity

- Existing sensors observing mechanics/hydraulics do not see anomalies (e.g., vibration/pressure)
- Integrate acoustic sensors into the monitoring system

## Two-step Approach

- Anomaly detection: profile baseline operation and find anomalies
- Sound localization: find the source of anomalies

Sound Event Localization and Detection of Overlapping Sources Using Convolutional Recurrent Neural Networks

Sharath Adavanne, *Member, IEEE,* Archontis Politis, *Member, IEEE,* Joonas Nikunen, *Member, IEEE,* and Tuomas Virtanen, *Member, IEEE*

ELSEVIER

Expert Systems with Applications

Volume 209, 15 December 2022, 118324

An anomalous sound detection methodology for predictive maintenance

Emanuele Di Fiore, Antonino Ferraro, Antonio Galli, Vincenzo Moscato, Giancarlo Sperlì

Very good

A Novel Measurement Information Anomaly Detection Method for Cooperative Localization

Bo Xu, Shengxin Li, Asghar A. Razzaqi, Yu Guo, *Graduate Student Member, IEEE,* and Lianzhao Wang

Sound Event Detection: A Tutorial

Annamaria Mesaros[1], Toni Heittola[1], Tuomas Virtanen[1], Mark D. Plumbley[2]

[1] Tampere University, Finland

email: {annamaria.mesaros, toni.heittola, tuomas.virtanen}@ tuni.fi

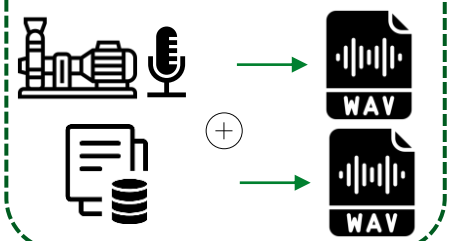
[2] University of Surrey, UK

email: m.plumbley@surrey.ac.uk

This one is amazing!

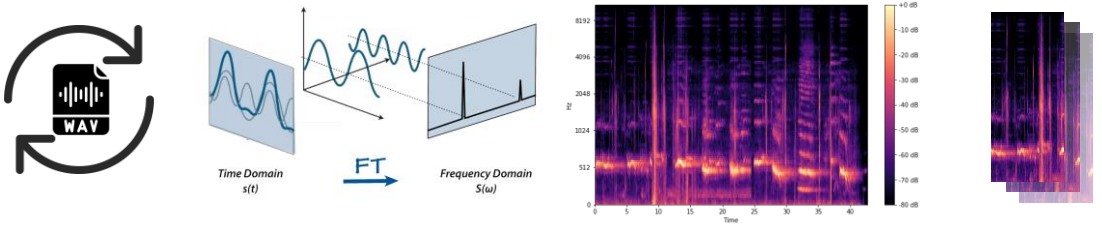
# Design & Approach

## Data acquisition



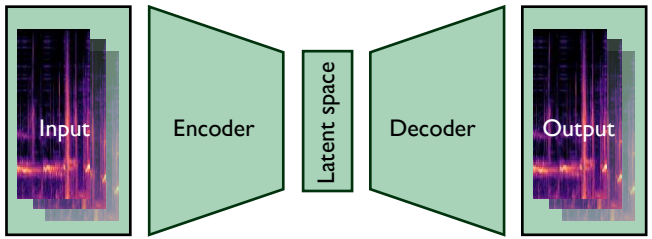

- Lab-test recording
- Dataset of machine sounds

## Data preprocessing

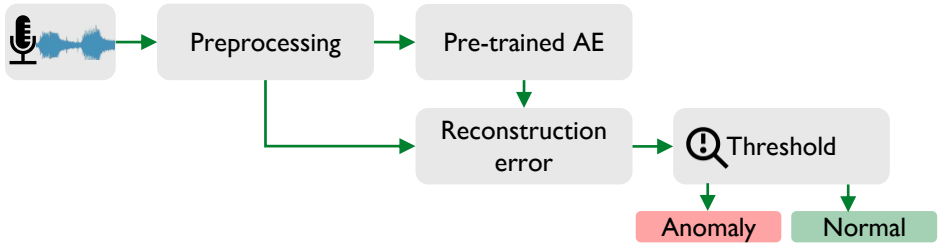



- Synchronization
- Short-term fourier transform
- Mel-scale transformation
- Normalization
- Frames generation

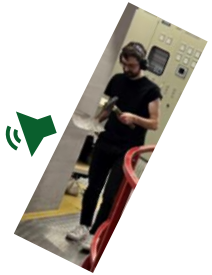
## Autoencoder training

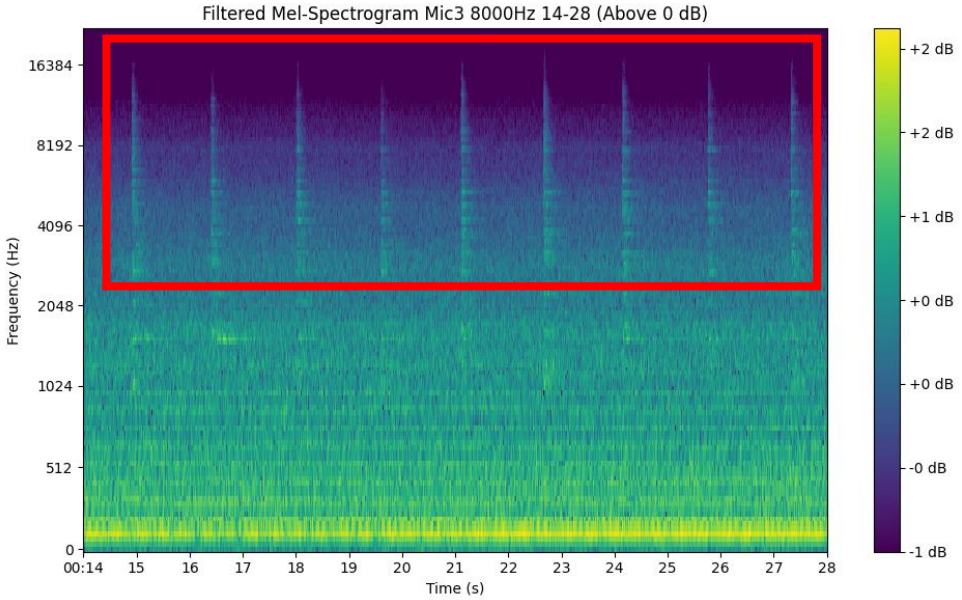


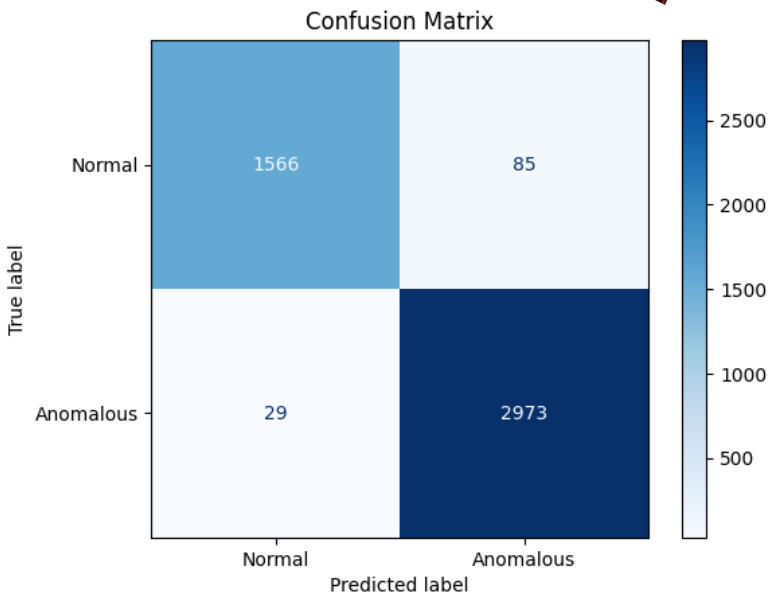

## Real-time deployment



# Preliminary Results – Induced Anomaly (Shovel+Hammer)

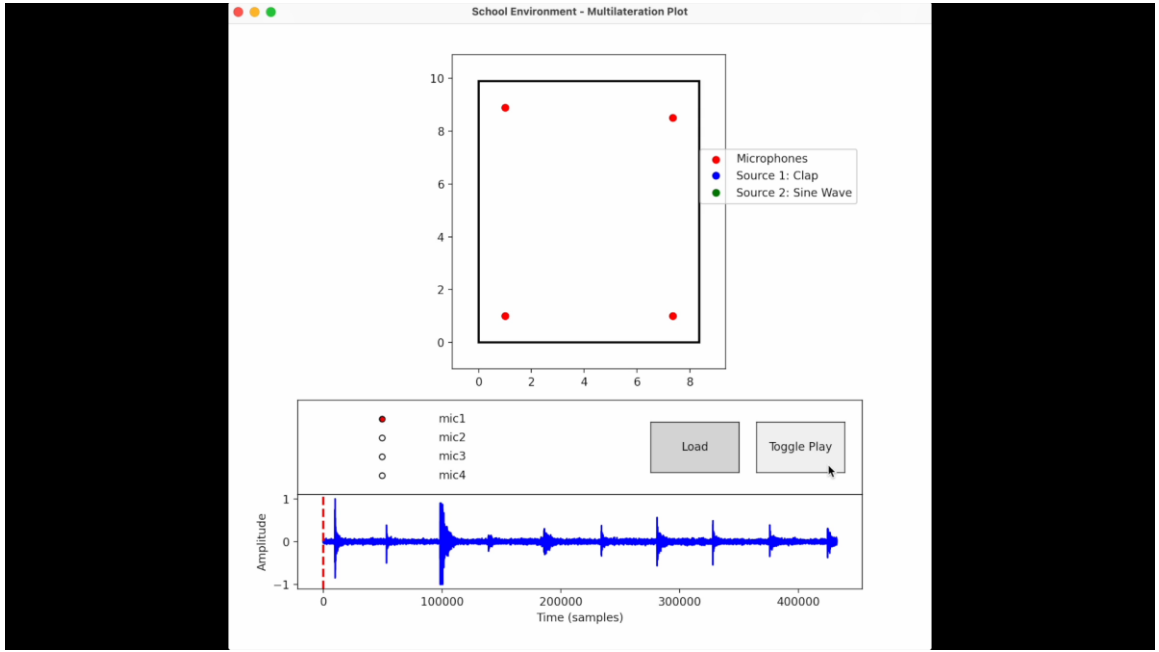




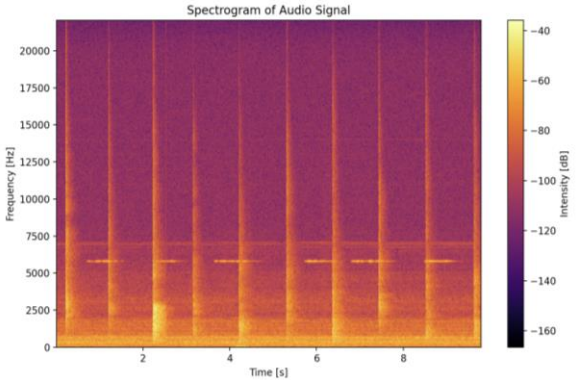




The shovel+hammer noise is straightforward to detect as anomalous

# Preliminary Results – Sound Localization



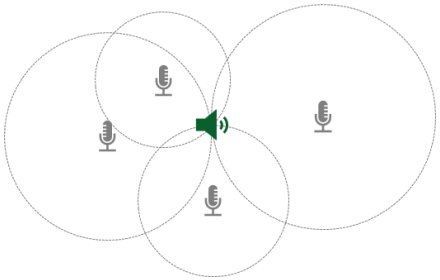

*Clapping while walking in a room with background music*



# 4. Closing

## Summary and Takeaways

# Major Takeaways



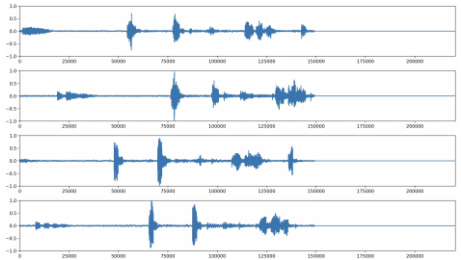
## Pros

- State-of-the-art ultrasonic sensors can detect minimal changes in noise frequency patterns
- Especially effective when anomalous noises are human-perceptible
- Non-invasive and adaptable to a wide range of applications
  - From rotating equipment to leak detection.

*Acoustic sensing is a mature and reliable technology, being ideal for applied settings where **precision** and **reliability** are needed.*

## Cons

- Relatively complex to model, which impact its cost benefit ratio over other sensors
- Sound localization is considerably more challenging than anomaly detection
- Performance may vary in noisy industrial environments, requiring advanced filtering and signal processing techniques.



# Questions?


Universität St.Gallen

**Prof. Dr. Bruno Rodrigues**
Assistenzprofessor

bruno.rodrigues@unisg.ch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