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Soundstripe

A Low-Cost Integrated Immunoacoustic Sensing Platform for Decentralized Biofluid Analysis in Resource-Limited Settings

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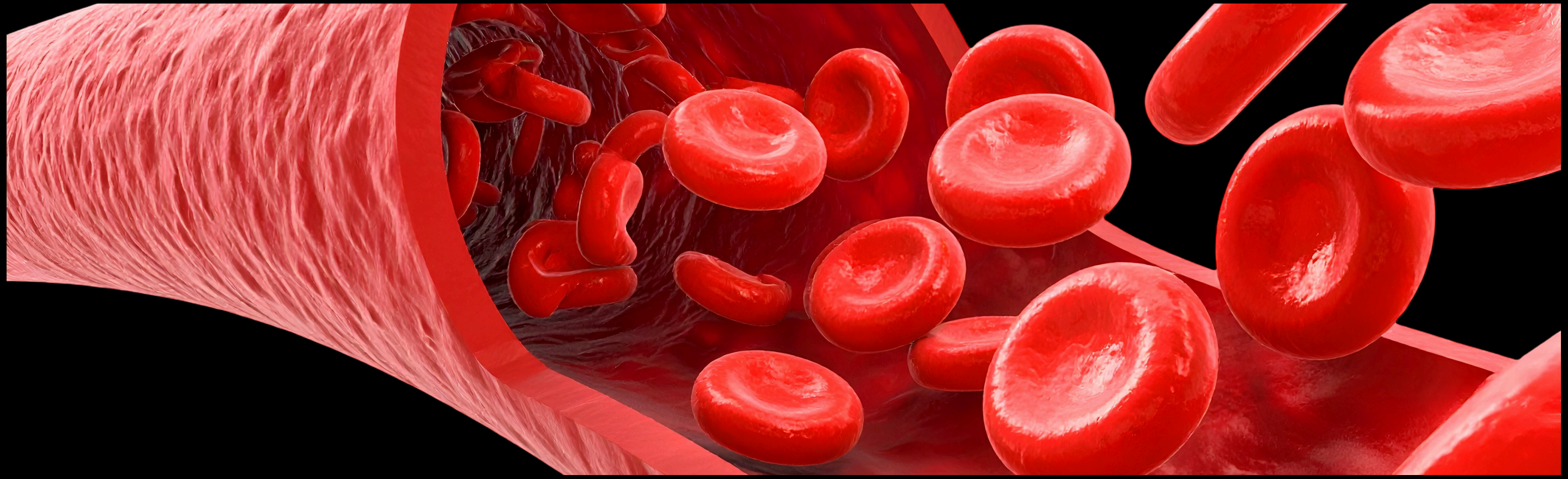
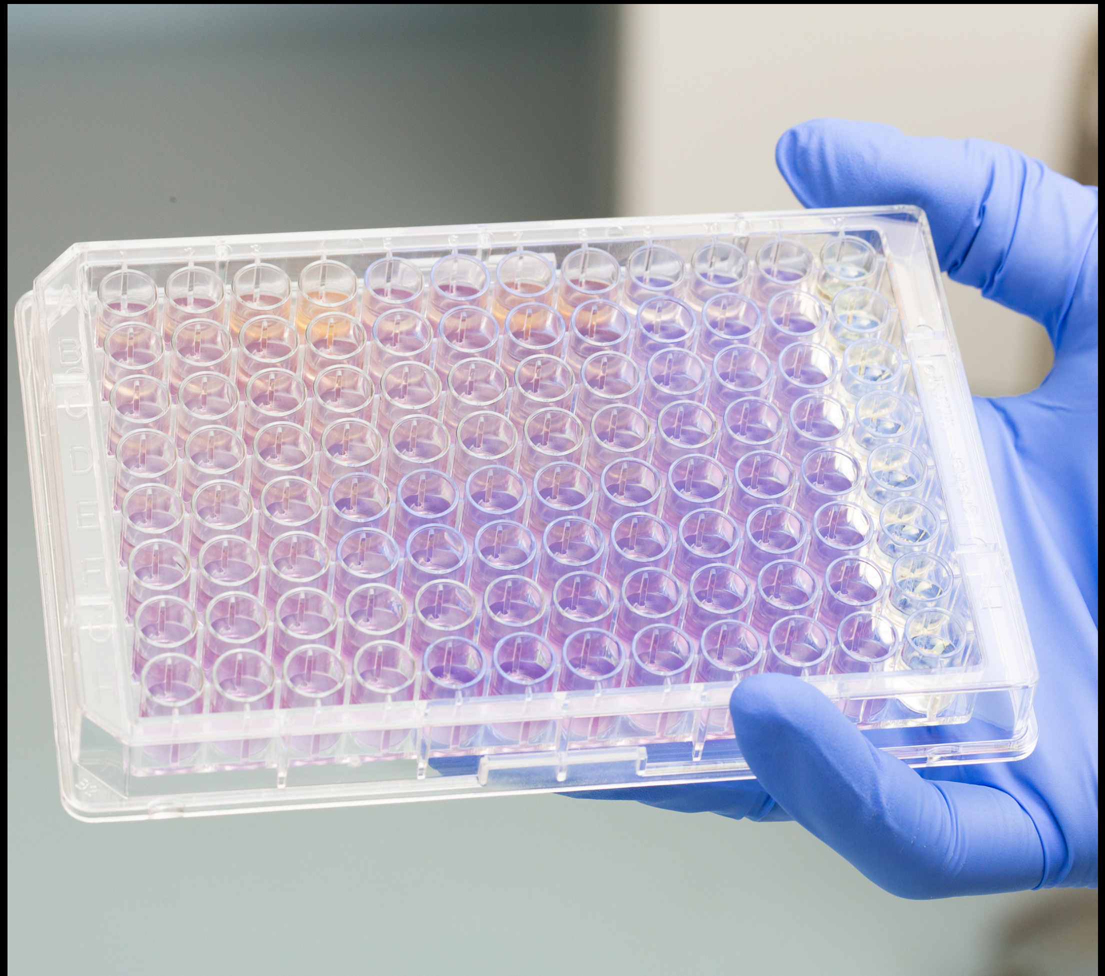
The Ideal

- Goal: Develop a low-cost, single-board acoustic system to analyze biofluid properties using sound and machine learning.
- Innovation: First integrated immunoacoustic PCB combining piezoelectric + MEMS sensing for droplet resonance analysis.
- Technology: 24-bit, ≥96 kHz acquisition; onboard MCU (RP2040/ESP32-S3); open-source hardware, firmware, and data pipeline.
- Science: Maps acoustic signatures → fluid parameters (viscosity, density, protein content) via ML regression/classification.
- Validation: Cross-verified with physical reference methods (viscometry, impedance spectroscopy).
- Impact: <$400 portable platform for decentralized, equitable biofluid diagnostics in resource-limited settings.
- Vision: A “stethoscope for fluids” — democratizing acoustic biosensing worldwide.

Introduction



Diabetes and related metabolic disorders affect over 537 million people worldwide, making improved health monitoring a critical need. Blood viscosity has long been used as a biomarker in disease; for example, elevated blood viscosity is observed in type 2 diabetes.



01 Conventional fluid assays (e.g. blood tests) often require invasive sampling, expensive equipment, and trained personnel, limiting their accessibility.

02 SoundStripe is a novel low-cost acoustic biosensor: it uses a paper cantilever to convert droplet impacts into sound, allowing noninvasive fluid property screening.

03 The device is tested using safe, water-based analog fluids (varying glycerol, protein, salt, surfactant) to simulate physiological changes without hazards.

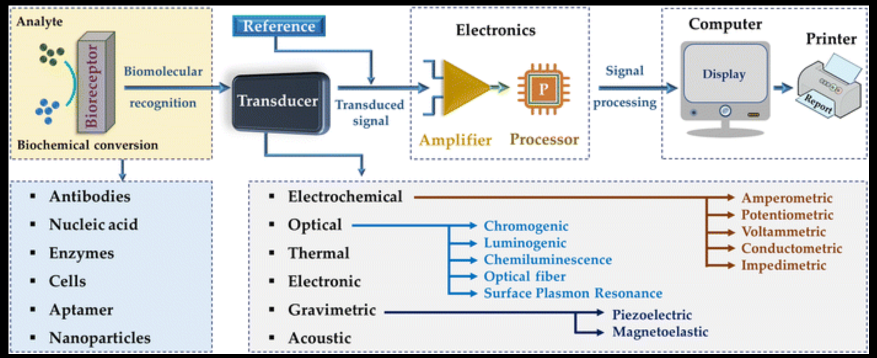
Research Question and Objectives

Can acoustic signatures from droplets on a paper cantilever be used to infer fluid properties (viscosity, density, surface tension) and distinguish “healthy” vs. altered fluid analogs?

The objectives:

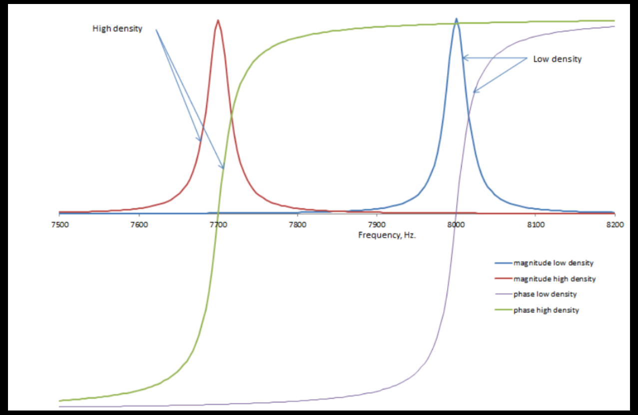
- Develop and assemble the SoundStripe platform (paper cantilever + piezo actuator + microphone) and establish baseline acoustic response.
- Systematically vary analog fluid composition (glycerol %, BSA, salt, surfactant) and measure resulting shifts in resonance frequency and damping. Higher density/viscosity fluids should lower the resonant frequency and increase damping.
- Extract signal features (peak frequency, decay time constant, amplitudes) and train machine learning models (e.g. random forest, neural network) to map these features to fluid properties or classify “healthy” vs. altered conditions.

Review of Related Literature



Literature Review 01

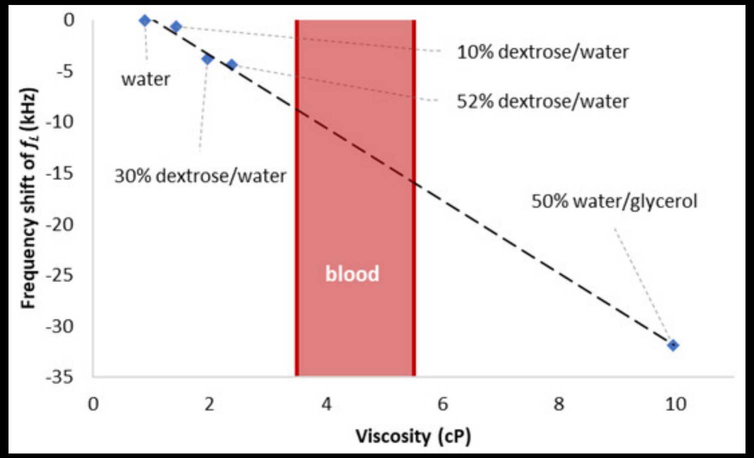
- Paper-based diagnostics (dipstick tests, lateral-flow assays, µPADs) are low-cost, versatile platforms for small-volume fluid analysis. They can accommodate tiny sample volumes through patterned barriers on paper.



Literature Review 02

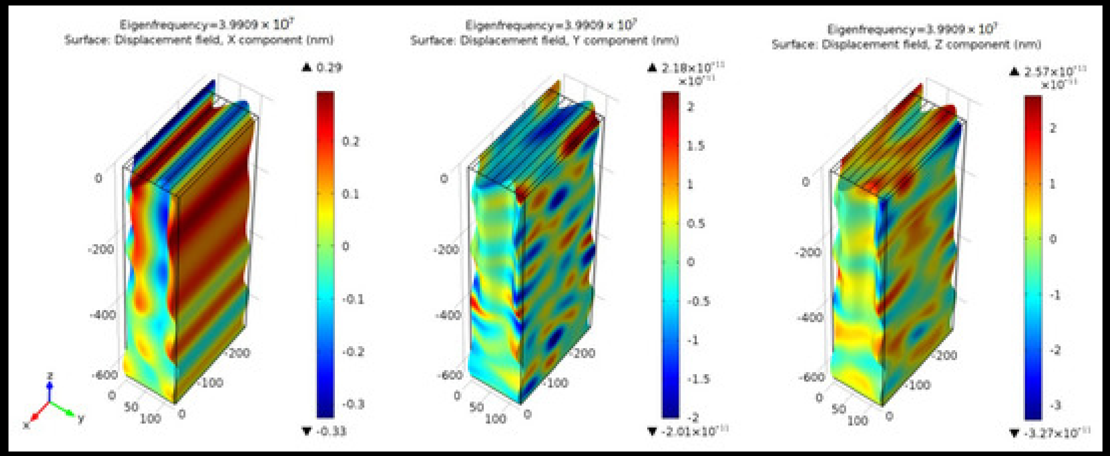
Vibrating resonator sensors (e.g. cantilevers, QCM) detect fluid density and viscosity by how added mass and viscous damping shift their resonance. In such sensors, denser fluids load more mass (lowering f_0) and higher viscosity increases energy dissipation (increasing damping).

Review of Related Literature



Literature Review 03

- Surface acoustic wave (SAW) devices have been applied to blood and plasma viscosity sensing: for example, a SAW biosensor measured blood viscosity from microliter droplets

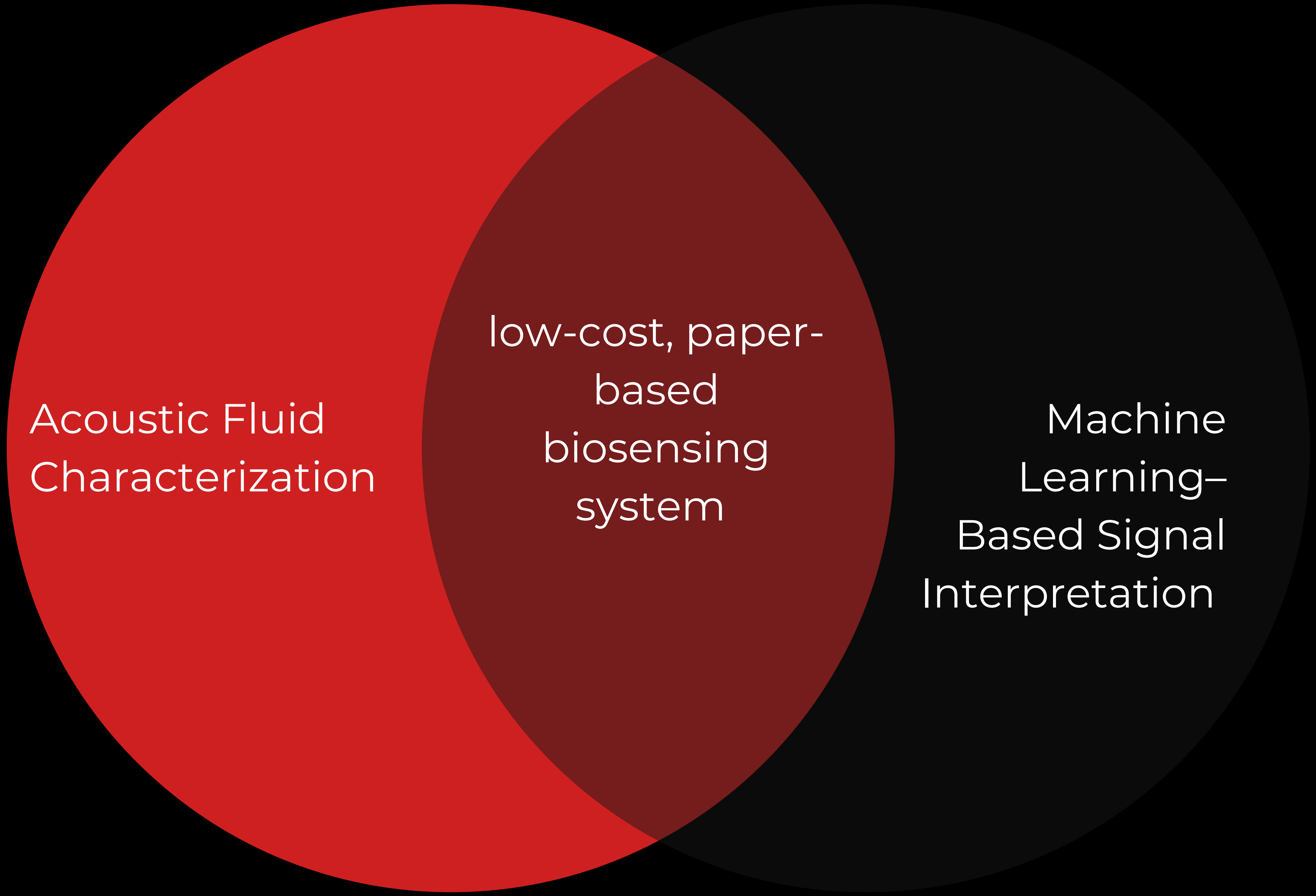


Literature Review 03

Acoustic biosensing often relies on time-domain and frequency-domain features of the signal (e.g. peak frequencies, decay envelopes). These approaches, combined with ML, have shown promise in extracting fluid-related information from sound.

Framework

A paper cantilever behaves like a damped spring that vibrates when struck by a droplet, heavier or more viscous fluids make it vibrate slower and die out faster. By measuring features such as peak frequency, decay rate, and signal energy, we can infer fluid properties like density and viscosity from its acoustic response.



Hypothesis

Hypothesis 01

Different fluid compositions produce distinct acoustic signatures on the paper cantilever.

Hypothesis 02

Higher viscosity or protein content lowers resonant frequency and increases damping.

Hypothesis 03

Altering surface tension (e.g., with surfactant) changes the initial impact amplitude and high-frequency content.

Research Methodology

Types of Research	Data and Source of Data	Collecting Data Technique	Data Analysis	Setting and participants in methodology
Experimental lab study to demonstrate an acoustic fluid sensor prototype.	Synthetic analogs: water + glycerol (0–50%), BSA (0–10 g/L), NaCl (0–1%), surfactant (0–0.1%). Primary data: acoustic waveforms (MEMS mic). Environment logged with a DHT22.	30×6×0.5 mm paper strips clamped as cantilevers. Deposit 10 μL, apply 200 μs piezo pulse, record ~1 s in a foam enclosure. 18 conditions × 10 repeats = 180 trials + dry baselines.	Extract FFT peaks, envelope decay (τ) and Q, RMS, spectral centroid. Train models (linear regression, random forest, small NN); evaluate R^2/RMSE and accuracy/ROC-AUC. Convert best model to TFLite for ESP32 deployment.	Bench-top lab with DIY hardware (3D-printed jigs, ESP32). No human subjects. Controlled acoustic enclosure and logged environment.

Scope of Research

- Domain: This work lies in bioinstrumentation and point-of-care diagnostics, emphasizing fluid mechanics, acoustics, and AI. It is primarily a proof-of-concept demonstration.
- Focus: The study focuses on qualitative screening of fluid properties (viscosity, density, surface tension) via acoustics, not on identifying specific chemical concentrations.
- Limitations: Experiments use water-based analogs instead of actual blood or biofluids, to avoid biosafety hazards. Environmental variables (temperature, humidity) are recorded but must be carefully controlled or calibrated out. This approach detects bulk fluid changes, not individual biomarkers.

Implementation

The setup uses low-cost tools (3D printer for jigs, MEMS mic, ESP32) to ensure reproducibility. Challenges include consistent droplet placement and ambient noise; these were addressed by using pipettes for uniform drops and a foam box to dampen external sound.

Phase 01

Build and calibrate: cut/mount paper cantilevers, attach piezo and MEMS mic inside foam enclosure, record dry baseline.

Phase 02

Run factorial tests for all glycerol/BSA/salt/surfactant combos; deposit 10 µL, actuate, record, replace strips, and log environment.

Phase 03

Process signals to extract features, train and validate ML models, report metrics (confusion matrix, R^2, ROC-AUC), and deploy the best model on the ESP32 (TFLite).

Theoretical Findings

1. Resonant frequency (mass + surface tension effect):

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k_0 + \gamma\sigma}{m_p + \alpha\rho V}}$$

- m_p = paper mass, V = fluid volume, ρ = fluid density
- k_0 = dry cantilever stiffness, σ = surface tension, γ = surface-tension coupling
- α = effective mass coefficient

2. Quality factor / damping (viscosity effect):

$$Q = \frac{\sqrt{(k_0 + \gamma\sigma)(m_p + \alpha\rho V)}}{c_0 + \beta\eta} \quad \Rightarrow \quad \tau_{\text{env}} = \frac{2Q}{\omega_0}$$

- c_0 = structural damping, η = fluid viscosity, β = damping coefficient
- τ_{env} = envelope decay time constant

3. Initial amplitude (surface tension + inertial impact):

$$A_0 \approx \frac{F_0(\rho, \sigma, v)}{k_0 + \gamma\sigma} \quad \text{with} \quad F_0 \sim \rho V v^2 + \sigma L$$

- v = droplet velocity, L = characteristic length of impact
- Captures the effect of both fluid inertia (mass/density) and capillarity (surface tension) on the initial waveform

Finding 01

- Mass loading: heavier/denser fluids lower the cantilever's resonant frequency.

Finding 02

- Viscous damping: higher viscosity shortens decay time (τ) and reduces Q.

Finding 03

- Surface-tension effects: surfactants change initial impact amplitude and high-frequency content.

Q&A Session

Thank you for the time and attention!

Links

- https://www.mdpi.com/1424-8220/23/13/5911 - SAW biosensors for blood viscosity, acoustic fluid sensing validation
- https://pubs.rsc.org/en/content/articlehtml/2024/ma/d3ma01019h - Paper-based microfluidic diagnostics, low-cost platform precedent
- https://rheonics.com/wp-content/uploads/2017/10/rheonics-vibration-sensor-whitepaper.pdf - Vibrating resonator physics, mass loading and damping principles
- https://www.tensorflow.org/lite/microcontrollers - TensorFlow Lite documentation, ML model deployment on ESP32/RP2040
- https://chat.openai.com - ChatGPT (GPT-4), mathematical equation rendering