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Deep Learning-Enhanced Density and Viscosity Sensing with Piezoelectric MEMS Resonators for Edible Oil Monitoring

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Summary:

Micromachined plates of varying dimensions, actuated by Aluminum Nitride (AlN) piezoelectric films served as density and viscosity sensors for monitoring edible oils. By analyzing multiple resonances, we obtained valuable insights into the liquid properties. We harnessed machine learning techniques integrated into a low-cost microcontroller board, which also facilitated excitation and data readout through straightforward conditioning electronics. During the training and calibration process, we utilized blends of various vegetable edible oils, explored several device geometries, and compared calibration errors and resolutions. Our findings underscore the substantial potential of this affordable sensor in accurately monitoring the density and viscosity of vegetable oils as an autonomous Internet of Things (IoT) and edge artificial intelligence system.

Keywords: MEMS, Piezoelectric, Machine Learning, Density, Viscosity, IoT.

Background, Motivation and Objective

The integration of machine learning with sensor technology has revolutionized the field of assisted systems, enabling the development of intelligent sensors that can adapt and respond to complex data patterns. Specifically, piezoelectric MEMS have emerged as a pivotal technology for density and viscosity measurements, offering high sensitivity and reliability in various applications, including wine fermentation or engine oil monitoring [1,2]. In the context of edible oil quality, olive oil is particularly susceptible to adulteration, necessitating robust monitoring techniques. This presents a multifaceted challenge, primarily due to the complexity of its composition and the prevalence of adulteration. The chemical profile of olive oil, which includes a wide range of volatile and phenolic compounds, is sensitive to numerous factors such as variety, geography, and processing methods. Ensuring the authenticity and purity of olive oil requires sophisticated analytical techniques, often involving chromatography and mass spectrometry, which can be costly and time-consuming. Furthermore, the industry faces the need for harmonization of quality standards and the development of more accessible, rapid testing methods that can be used outside of specialized laboratories. The recent advancements in sensor technology and machine learning offer promising solutions to these challenges, enabling the detection of oil quality with greater accuracy and efficiency. However, the implementation of such technologies on a wide scale is still in progress, and continuous research is needed to refine these methods and make them more affordable and user-friendly. The goal is to protect consumers and producers alike, ensuring the olive oil on the market is of the highest quality and free from fraudulent practices. This work aims to explore the potential of deep learning-enhanced piezoelectric MEMS sensors in the precise monitoring of edible oils, with a focus on detecting changes in viscosity and density in olive oil.

Description of the New Method and System

Figure 1 shows the experimental setup that can be used in both static and flow-through modes, with the MEMS resonator in the fluid cell, microcontroller (MCU) and signal conditioning circuit. The micro-plates were designed to maximize certain out-of-plane modes and fabricated with the PiezoMUMPS foundry process. In this work, two top electrodes connected in parallel (+) were used as actuation ports and the other two (-) as sensing ports. The MCU, a versatile module equipped with Wi-Fi and Bluetooth® Low Energy capabilities, was programmed to generate and gather sensor signals. These signals were processed through a simple transistor-based conditioning electronic system, which operates within a frequency range of 20kHz-1MHz. For each frequency, the envelope of the amplified sensor output signal was recorded, leading to the identification of several resonances that are sensitive to the physical properties of various oils. A calibration protocol was established using blends of two oils, each characterized by distinctly different properties, and their spectra were gathered into a database which served as the foundation for training a Convolutional Neural Network (CNN) model. This was then implemented into the MCU to accurately estimate the targeted properties without relying on cloud-based computations. Furthermore, the dimensionality reduction performed by the model was studied as a potential enhancement to decrease both the time required for capturing spectra and the resource usage of the MCU. This could lead to more efficient and faster analysis. Various combinations of hyperparameters were examined to optimize the model's performance in terms of calibration and resolution errors. The model's utility is not confined to the calibration liquids and can be generalized to differentiate between oils and mixtures derived from different seeds.

Results

Fig. 2 shows the spectra obtained at room temperature (25 ºC) with the sensing system of Fig. 1, in static mode, for the oils listed in Tab. 1. The data were acquired by circulating the liquids through the fluidic system for 3 min to allow the uniform filling of the cell cavity, with no further cleaning between them except for air flow, and then waiting for some minutes (depending on the specific oil measured) until stabilization in the measurement. This figure shows the resolution of the proposed system to identify different varieties of oils, as well as the potential for detecting mixtures among them. Furthermore, it highlights the feasibility of applying a machine learning model as an estimator of viscosity and density properties.

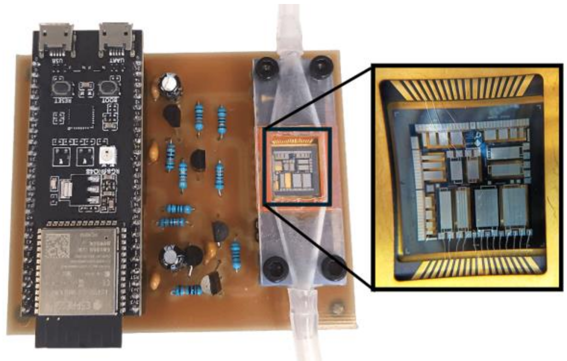

Fig. 1. Schematics of the complete system with the Espressif ESP32-S3 MCU on the left and packaged MEMS inside the fluid cell on the right side.

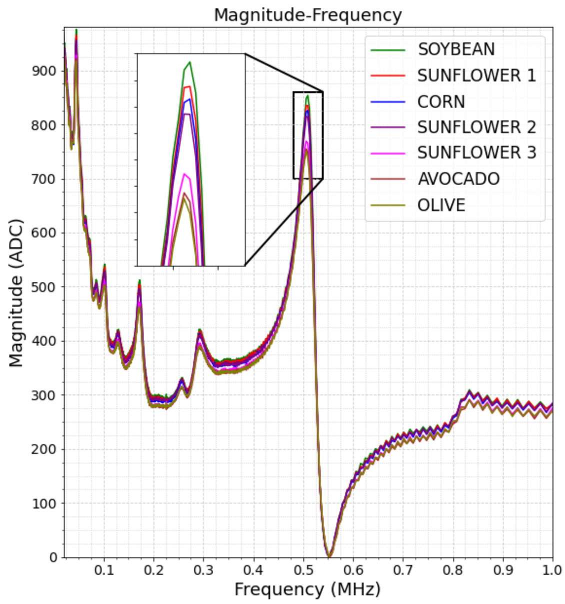

Fig. 2. Spectra of some food oils captured with the proposed system.

Tab. 1: Dynamic viscosity and density of different vegetable oils.

Oil	Viscosity (mPa·s)	Density (g/mL)
SOYBEAN	58.870	0.920
SUNFLOWER 1	60.481	0.919
CORN	62.863	0.919
SUNFLOWER 2	65.045	0.918
SUNFLOWER 3	76.576	0.913
AVOCADO	77.581	0.913
OLIVE	78.480	0.912

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