Mentors: Dr. Fadwa El Mellouhi, Dr. Harris Rabbani

Team: Aziza Mohammed, Ahyen Mostofa, Dr. Usman Chaudhry, Yasmin Abdelkarim, Souhil Sid , Rehaan Hussain,
Affiliation: AISCIA Informatics, Doha, Qatar

Digital Bubble Stability tracking microscope

Objective

This project develops an interpretable, data-driven framework to predict foam structural evolution and stability from microscopy data without requiring live microscope access. Using real HBKU experiments, experiment-known inputs are mapped to bubble-scale descriptors and realistic visual surrogates, supporting efficient CO_2 foam stability analysis for CCUS applications.

Background and Motivation

CO_2 foams are widely used in CCUS applications to reduce gas mobility and improve sweep efficiency in subsurface formations. Their effectiveness, however, is limited by instability mechanisms such as bubble coarsening, gas diffusion, drainage, and film rupture. These microscopic processes directly determine macroscopic foam lifetime and performance.

Data and Inputs/Outputs

Model Inputs (experiment-known)

- Time (s)
- Surfactant weight fractions: coco betaine, coco glucoside, capryl glucoside, coco-B
- Nanoparticle Al_2O_3 wt.% (0 for legacy data

Model Outputs (image-derived targets)

- Bubble count density (per mm²)
- Mean and standard deviation of bubble area
- Characteristic radius: Ravg, Rrms, R21, R32
- Morphological metrics v and w
- Lamella thickness (mm)
- Foam half-life (s)

Methodology

Regression Modeling with Aiscia Platform

We employ a **Random Forest Regressor (RFR)** to map tabular experimental inputs to bubble-scale structural descriptors. The model was trained using the **Aiscia Platform**, powered by **AISCIA Informatics (Doha, Qatar)**, which streamlined data preparation, feature handling, and rapid model iteration.

Model configuration: - RandomForestRegressor with 280 trees - Maximum depth: 6 - Train/test split: 0.79 - Random seed: 42

Inputs used: time_s, surfactant weight fractions, and nanoparticle_al2o3_wt_pct

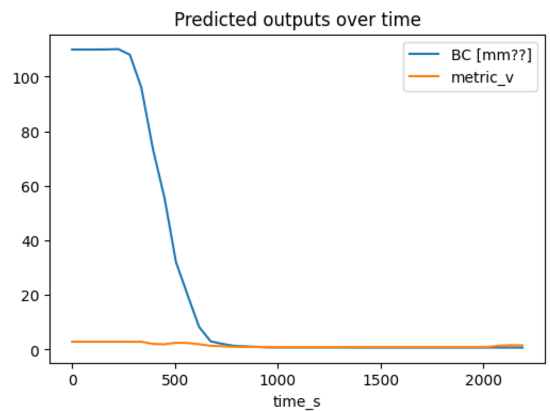
Performance: - Training R^2: 0.8684 - Test R^2: 0.7722

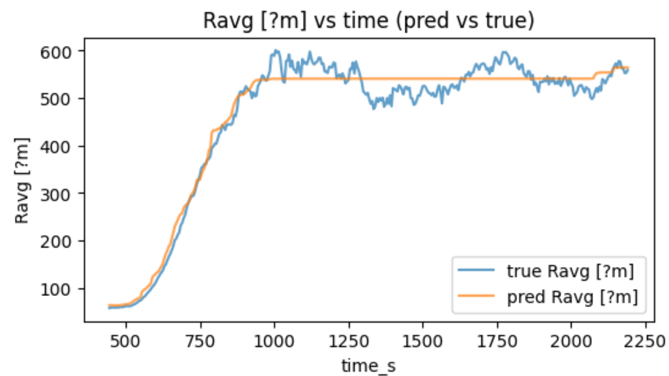
The RFR provides an interpretable and robust baseline for predicting foam structure across both legacy and nanoparticle-enriched datasets.

Nearest-Neighbor Microscopy Frame Simulation

To generate visual outputs, predicted bubble descriptors are normalized and embedded in feature space. A k-nearest-neighbor (k-NN) search is then used to retrieve the closest real microscopy frame from the H5 image pool.

Key variants include: - Composition-locked retrieval to avoid cross-mixture artifacts - Nearest-time mapping to improve temporal smoothness - Global all-frame matching for broader visual coverage.



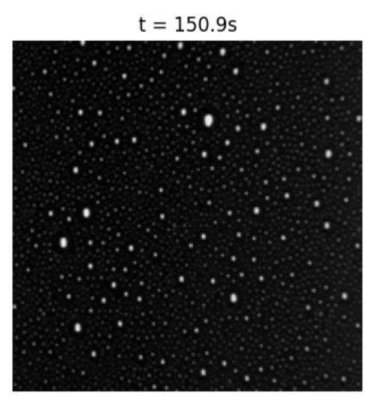


Validation and Results

Model performance was evaluated on held-out test data using RMSE, MAE, R^2, and Hit@10% metrics. Macro R^2 values range from approximately **0.6 to 0.9** depending on the target, with the strongest performance observed for radius-based descriptors.

Side-by-side comparisons of real and simulated microscopy frames demonstrate that nearest-neighbor mapping yields visually plausible bubble structures.

Digital Data Compatibility and Microscope Integration



This workflow is designed to be fully compatible with the hackathon’s digital data management infrastructure, using HDF5 (H5) as both the input and output format. Microscopy image stacks are ingested directly from H5 containers, and predicted or simulated frames can be written back in the same format, enabling seamless integration with digital microscope platforms, including the Oak Ridge digital microscopy ecosystem.While demonstrated on optical foam microscopy, the H5-native, instrument-agnostic design makes the approach readily extendable to AFM, SEM, and STEM modalities.

Conclusion

We present an end-to-end, digital microscopy analysis pipeline that transforms practical laboratory inputs into quantitative foam descriptors and realistic visual surrogates. Leveraging real HBKU datasets, an interpretable Random Forest model on the **Aiscia Platform**, and composition-aware nearest-neighbor image simulation, this workflow reduces the cost and complexity of foam stability analysis.