CHARACTERIZATION OF FOAM BUBBLES IN POROUS MEDIA

3D ANALYSIS OF FOAM BUBBLES USING A LARGE NOSQL DATABASE
OUTLINES

- Context
- Data Description & Management
- Workflow
  - Preprocessing
  - Segmentation
  - Analysis
  - Statistics
- Conclusions
This work was initiated by at first the research on the use of foam in oil recovery (EOR).

The foam is known to be a good agent for controlling the mobility of gas by overcoming the problems posed by the latter in terms of gravity segregation and viscous digitation.

The mobility of foamed gas in porous media originates from its pore-level microstructure.

The aim of this work is to describe and understand foam flows in porous media.

One of the challenges is to link macroscopic petro-physical measurements to local measurements for flows in real three-dimensional porous media.
MicroTomography Experiment  
- performed at the ID19 beamline at the European Synchrotron Radiation Facility at Grenoble, France.

The main difference between synchrotron light and the X-rays used in labs is the brilliance.  
- a synchrotron source is one hundred billion times brighter than lab’s X-ray sources.  
- The higher the brilliance, the more precise the information that can be obtained from the X-ray.  
- The result is images with high spatial (0.55) and temporal resolution (1 second per tomography cube).

Numerous images  
- The main drawback of such images is how representative the small observed areas are.  
  - Many areas need to be imaged.  
- The trapping phenomenon (mainly responsible for the behavior of the foam) is an intermittent phenomena.  
  - Images over long laps of time are required.

Getting experiment time on these “big instruments” is limited and rare.  
- It is the first time that a foam flowing can be observed in situ.
Each acquisition produces a 3D volume (a "Cube")
Described by an header, and some raw binary data for pixel intensity

```json
{
  'experience': 'cell1',
  'name': '_1.1_microcell1_112_150_35keV_1s_gaz_TA_fg50_haut_ ',
  'numero': 24,
  'pixel_size': [1.1, 1.1, 1.1],
  'position': [0.1, 0.27, 28.0],
  'projet': 'TMI',
  'serie': 0,
  'timestamp': datetime.datetime(2017, 11, 25, 5, 3, 18),
  '_id': ObjectId('5c1a405c8522f34234ef1eed'),
  'cube_id': ObjectId('5c1a40248522f34234ef0f99'),
  'cube_size': [1008, 1008, 1008],
  'cube_type': 'uint8',
}
```
COLLECTION OF CUBES

- Many acquisitions at numerous time steps
- Collection of more of thousand cubes.
  - Some are related to single acquisition
  - Some represents series
- Stored using GridFS from MongoDB on an Hadoop cluster.
- Need an automatic way to analyze each cube and all statistical data collected during collection processing.
  - Use python to aggregate classical scientific tools and image algorithms to manipulate these cubes

- Python
  - Pymongo
  - Ndimage
  - Scikit-learn
  - Ctype (IFPEN GPU code)
Objective: Recognize what a bubble is and how it can be segmented/isolated from other part of the image using its attributes

**Preprocessing**
- Acquisition denoising: removes geometric artifacts
- Filtering: increases signal/noise ratio – Anisotropic filtering

**Segmentation:**
- How to separate the different phases of the noise free 3D image. For the reminder, the four phases involved are the "bubble", "flowing zone", the “water" and the "mineral / rock" phase.

**Analysis**
- In “bubble” phase only, labelling each individual bubble from each others

**Statistics**
- Describes and try to classifies “bubbles” using some attributes.
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PREPROCESSING : DENOISING (1)

- Mean signal is heterogeneous against z

Mean and Standard deviation of pixel intensity for each z plane
PREPROCESSING : DENOISING (2)

On each z plane, radial inhomogeneous signal: dome effect

Mean pixel intensity by summing over z

Non linear Least Square fitting

Mean pixel intensity by summing over radial angles

Fitted mean pixel intensity

Fitted z image of gain
PREPROCESSING : DENOISING (3)

Before

After
WORKFLOW

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Each phase has a characteristic pixel intensity
Noise, or material variability gives a specific distribution (or mode) for each phase
Try to narrow pixel distribution for « bubble » and « matrix » phase.
Low-pass filter that preserves discontinuities ( border ) - Flowing Bilateral 3D filter on GPU

PREPROCESSING: FILTERING (2)

Before

After
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SEGMENTATION : BASED ON HISTOGRAM (1)

- Histogram fitting to find pixel distribution of each phase
- Non linear gaussian mixture fitting to estimate proportion, mean and standard deviation of pixels in each phase

<table>
<thead>
<tr>
<th></th>
<th>Foam</th>
<th>Water</th>
<th>Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportion</td>
<td>0.175</td>
<td>0.236</td>
<td>0.589</td>
</tr>
<tr>
<td>Mean</td>
<td>48.23</td>
<td>93.31</td>
<td>167.54</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>2.35</td>
<td>6.04</td>
<td>2.30</td>
</tr>
</tbody>
</table>
Naive bayes classification with low false positive rate

\[ p(C_k \mid x) = \frac{p(C_k) \cdot p(x \mid C_k)}{p(x)} \]

Computes for each pixel one posterior probability where
prior is given by estimated frequency \( p(C_i) \) and likelihood \( p(x \mid C_i) \) by estimated gaussian

Assign to each pixel class that has the maximum posterior probability if this probability is over a threshold
  - we are quite confident with this assignement

\[ \hat{y} = \arg\max_{i=1,2,3} p(C_i) \cdot p(x \mid C_i) \]
Compute image gradient using sobel filters

Compute Watershed on image gradient with Segmentation-1 results as seed markers.

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**ANALYSIS : FOAM BUBBLES SEPARATION**

- Method described by Pierre Soille
  - Only bubble phase of previous steps is kept as a binary image
  - Computes the euclidean distance transform on the binary image = minimal distance from the background considering a given connexity

- Pick and keep only some of the local maximas on this distance image.
- A specific label is assigned to each maxima
- Watershed is applied on distance image using these labels as marker seeds.

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So far, able to isolate 3D individual bubbles automatically.

Then process a large collection of “cubes” to characterize foam (=bubbles) in a poreous media.

In this example, can these bubbles be segregated in two classes?

One for well defined bubbles and another for fuzzy ones.

Extract some attributes on bubbles.

For each bubble:
- Its Volume (in pixel),
- Surface of its skin (in pixel)
- Mean pixel values (from original cube) on its support
- Standard variation of pixel values on its support
- Sphericity

\[
\frac{\sqrt[3]{V}}{\sqrt{S}} = \frac{\sqrt[3]{\frac{4\pi}{3}}}{\sqrt{4\pi}} \approx 0.45
\]
STATISTICS (2)

```json
{
  "cube": ["cell1", 137, 0, 68.],
  "proportions": [
    28.83076988330465,
    13.698114240901695,
    57.47111587579366
  ],
  "bubbles": {
    "1": {
      "volume": 1383,
      "mean": 47.29573440551758,
      "std": 13.9647855758667,
      "surface": 659,
      "sphericity": 0.43400828330527835
    },
    "6": {
      "volume": 3342,
      "mean": 72.24895477294922,
      "std": 8.165091514587402,
      "surface": 1532,
      "sphericity": 0.38197895068857846
    },
    ....
  }
}
```

- **Toy example**
  - 16 cubes [504, 504 504]
  - Gives 21740 bubbles
  - Once small bubbles removed
  - Once outliers removed
**Toy example**
- 16 cubes of half size [504, 504 504]
- Gives 20762 bubbles
- Once small bubbles removed
- Once outliers are removed using z_score less than 3

*Box plot for each normalized feature*
Toy example: Basic K-means classification to identify two classes.
CONCLUSION

Setting up a complete chain to homogeneously store all “cubes” and handle them using an unified and scriptable python process.

First time that foam in a porous media has been imaged and characterized at that scale.

But a better way to control automatic results is needed. How to ensure the quality of the segmentation? No labeled images so far, pure unsupervised learning.

Moreover according our preliminary results, there is no evidence of two real classes using these features and this segmentation process.

Need to push class information back to images

Able to do processing, but some time optimizations are now mandatory to analyze data at full resolution.
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