HELMHOLTZ AI | ARTIFICIAL INTELLIGENCE COOPERATION UNIT

Advanced distance measures for analysis of hybrid rocket combustion video data

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Outline

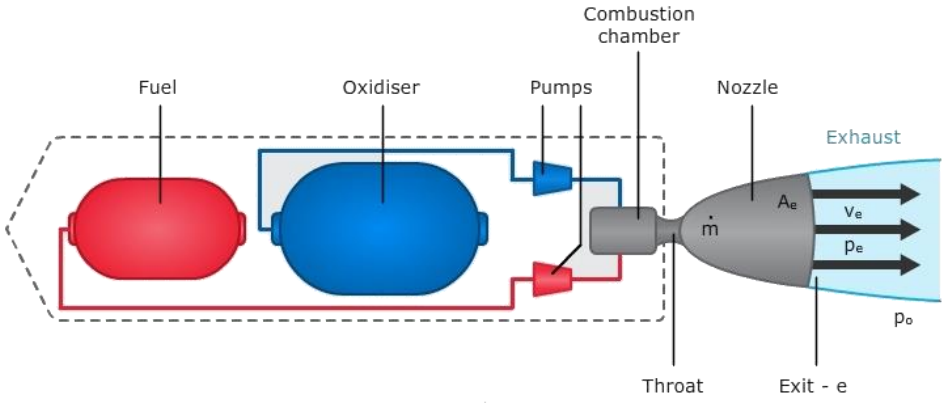
1. Rocket engine combustion analysis at DLR

2. Dissimilarity measures for images

3. Results
   a) Clustering
   b) Anomaly Detection

Rocket engine combustion analysis

Aim: Cost reduction of rocket engines, be competitive with e.g. Space-X

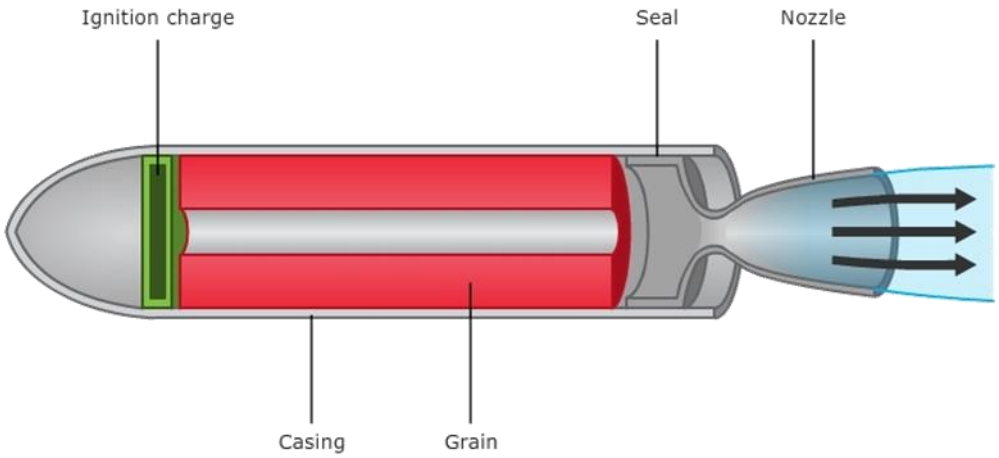


Traditional liquid rocket engine:

- 2 pumps transporting fluid fuel and oxidizer at very high pressure and flow
- Advantages
  - Burning rate can be controlled precisely
- Disadvantages
  - Pumps are mechanically very complex
  - Expensive

Rocket engine combustion analysis

Aim: Cost reduction of rocket engines, be competitive with e.g. Space-X

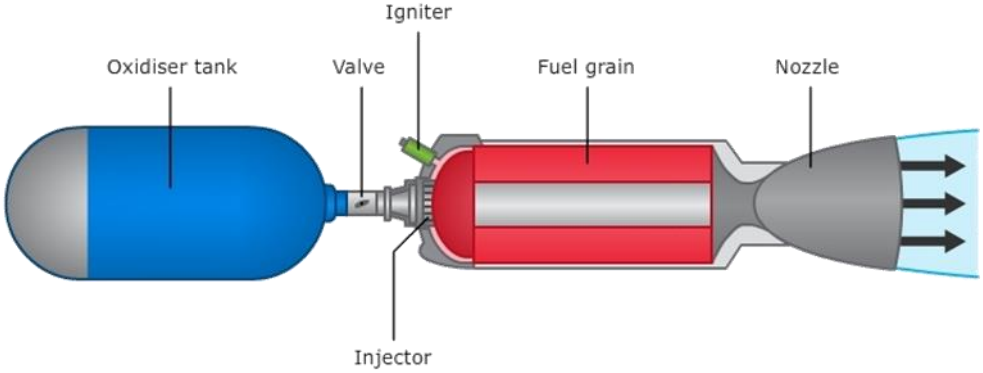


Solid propellant rocket engine

- Fuel and oxidizer are mixed in solid form
- Advantage
  - Cheap
- Disadvantage
  - Burning rate can not be varied during flight

Rocket engine combustion analysis

Aim: Cost reduction of rocket engines, be competitive with e.g. Space-X



Hybrid rocket engine

- Pressurized fluid oxidizer
- Solid fuel
- A valve controls, how much oxidizer gets into the combustion chamber

- Advantages
  - Cheap
  - Controllable

Experiments on new hybrid rocket fuels at DLR

- DLR investigates new hybrid rocket fuels on a paraffin basis at Institute of Space Propulsion in Lampoldshausen.
- About 300 combustion tests were performed with single-slab paraffin-based fuel with 20° forward facing ramp angle + gaseous oxygen.
- Combustion is captured with high-speed video camera with 10 000 frames / second

Fig. 1: Fuel slap configuration before (top) and after (bottom) combustion test.

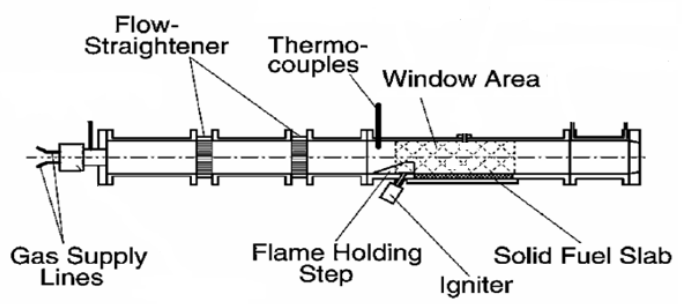


Fig. 2: Side view of combustion chamber

Test 284

Schlieren video:
(test extract)

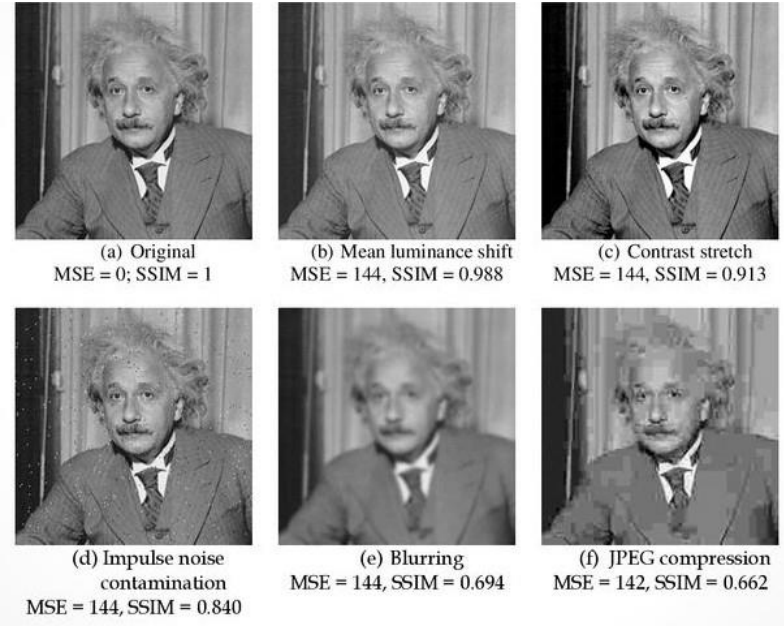
fuel = pure paraffin 6805
oxidizer mass flow = 50 *g*/*s*,
CH*-filter (i.e. wavelengths emitted from CH* are filmed)
test 3s = 30 000 frames / 8GB data per test

Helmholtz AI voucher

- AI voucher was requested by the DLR Institute of Space Propulsion in Lampoldshausen.
- **Aim:** Investigation and implementation of advanced distance measures such that an automatic analysis procedure can be developed.
- Data analysis that relys on adequate distance measures:
  - Clustering (i.e. determine different flow phases)
  - Anomaly detection (i.e. detect satellite droplets and irregular flow structures)

Dissimilarity measure for image data

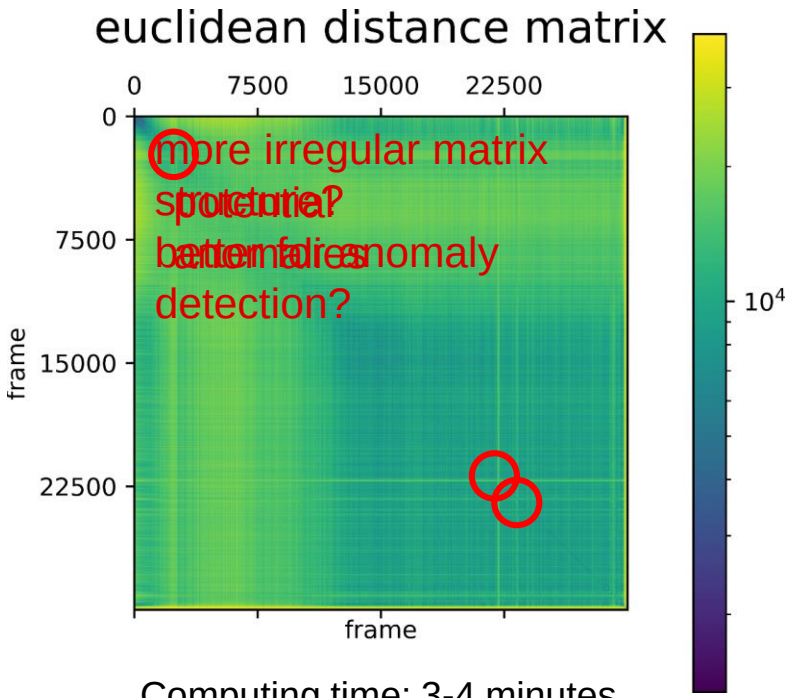
- Algorithms often require pairwise dissimilarity of images (matrix of size nr_of_images x nr_of_images).
- Standard approaches such as mean squared error (MSE) / discrete L2-norm often differ from human recognition.
- Advanced dissimilarity measures such as structural similarity (SSIM) often perform better but are much more expensive.
- Structural similarity (SSIM)/ structural dissimilarity (DSSIM) is not a distance metric.



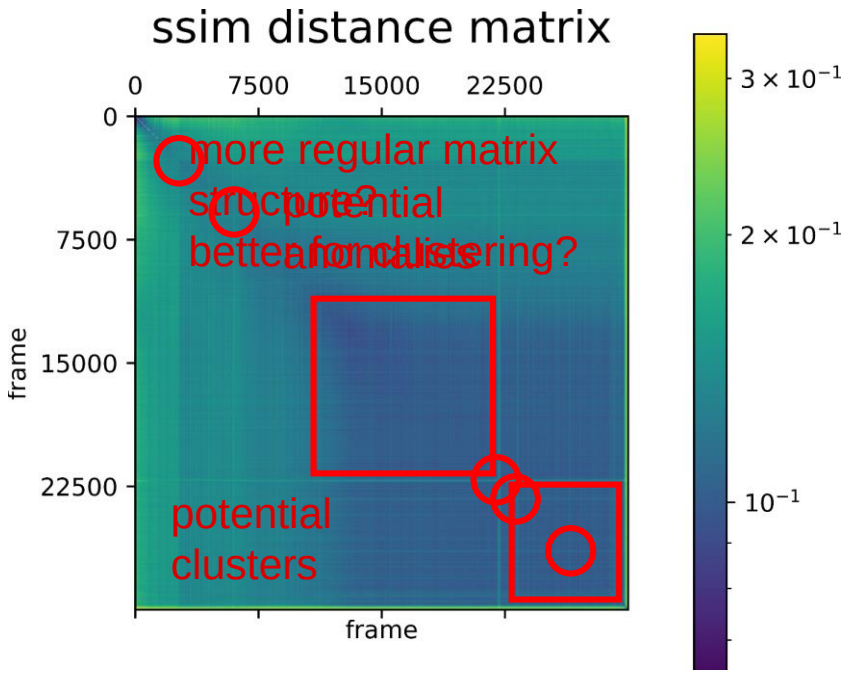
Example: (b)-(f) with same MSE, SSIM decreases*

*https://nsf.gov/news/mmg/mmg_disp.jsp?med_id=79419&from=

Pairwise distance matrices for test 284



Computing time: 3-4 minutes



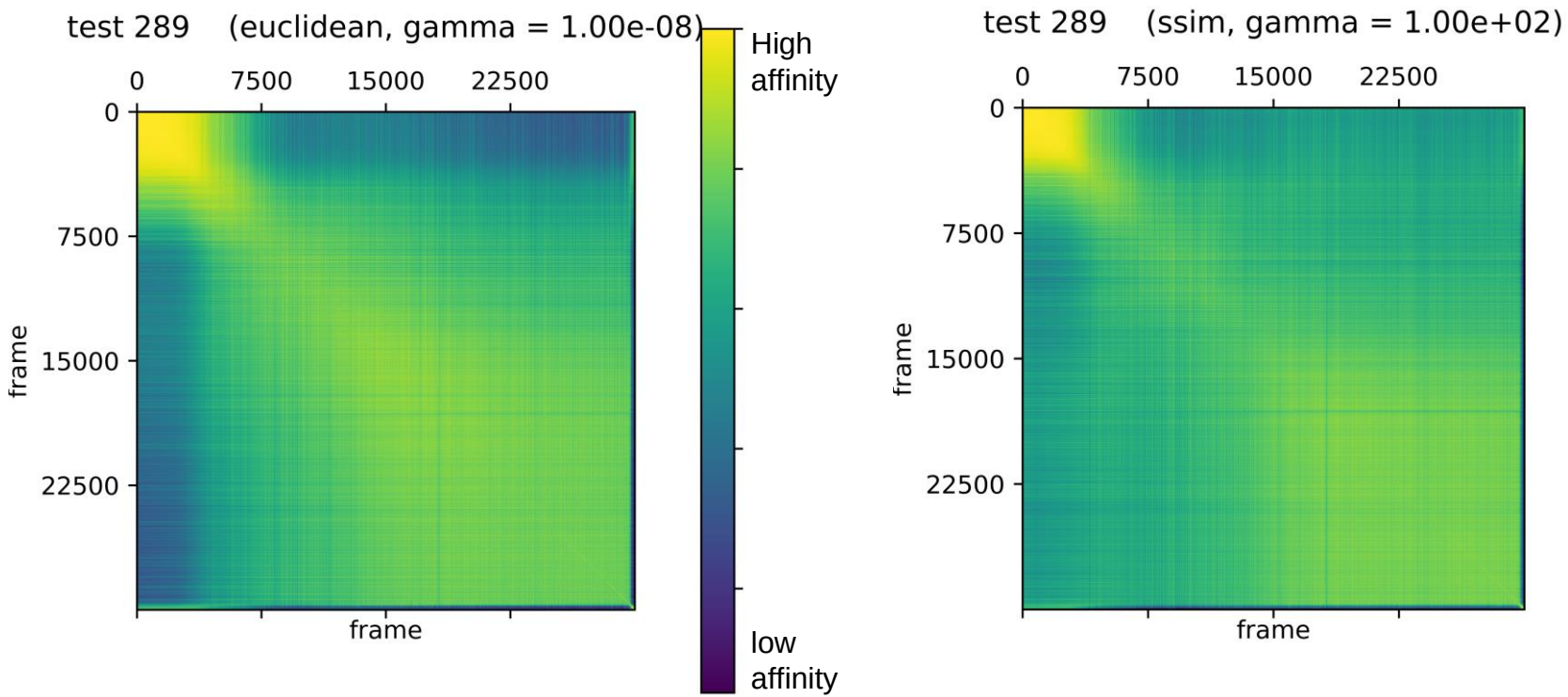
Computing time: 5 days (OpenMP parallel, 56 cores)
one comparison ≈ 0.1 s (scikit-image)

AI Voucher (2 months): List of computed pairwise distance matrices

Test with 30 000 images/test	**Euclidean**	**SSIM**
203	✓	✓
214	✓	✓
232	✓	✓
234	✓	✓
243	✓	✓
253	✓	✓
276	✓	✓
284	✓	✓
289	✓	✓
291	✓	✓
296	✓	✓

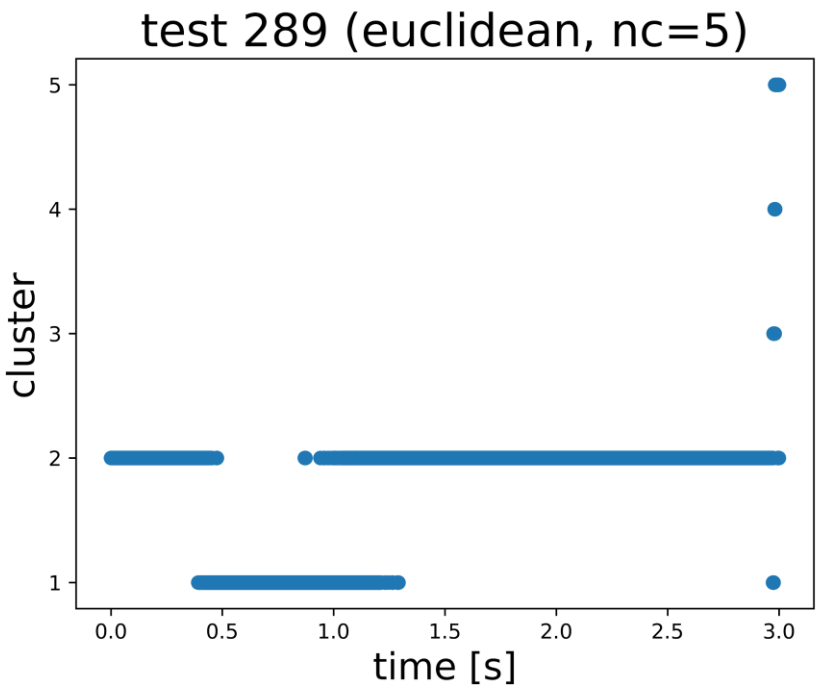
- Spectral Clustering with affinity matrix
- Anomaly Detection with Local Outlier Factor algorithm using distance matrix

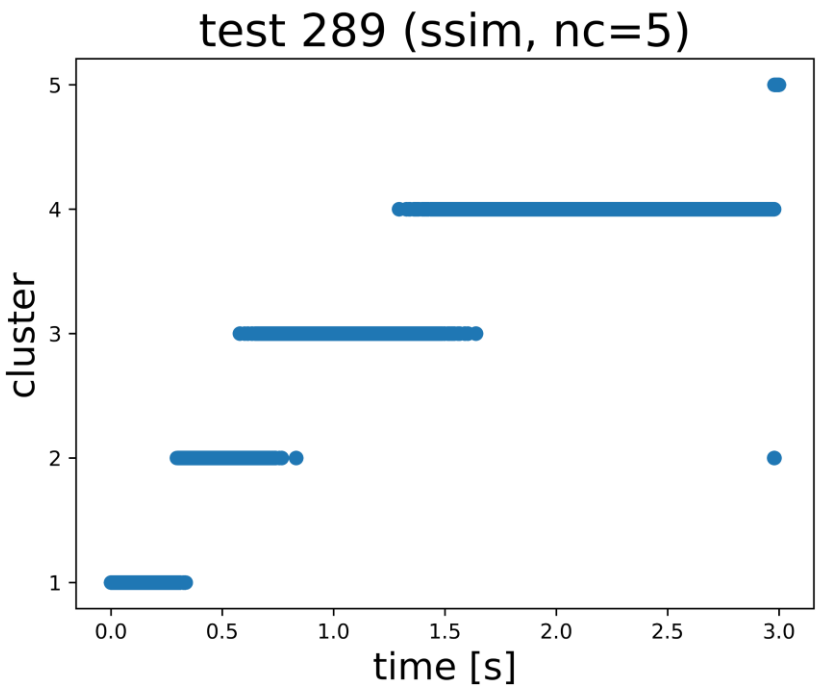
Spectral Clustering of test 289



Affinity matrices derived from pairwise distance matrices

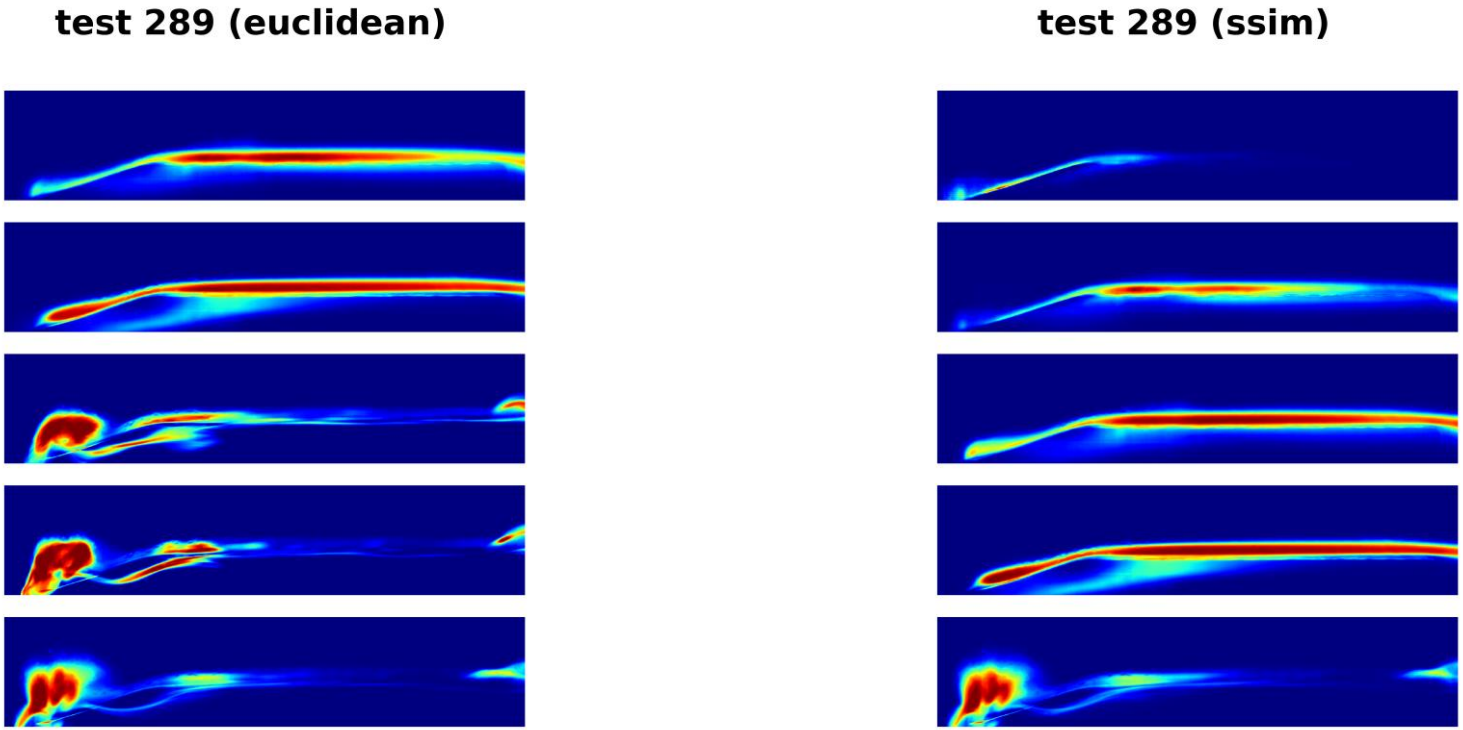
Spectral Clustering of test 289





Clustering results and visualization of the corresponding points in times

Spectral Clustering of test 289



Visualization of the cluster centroids

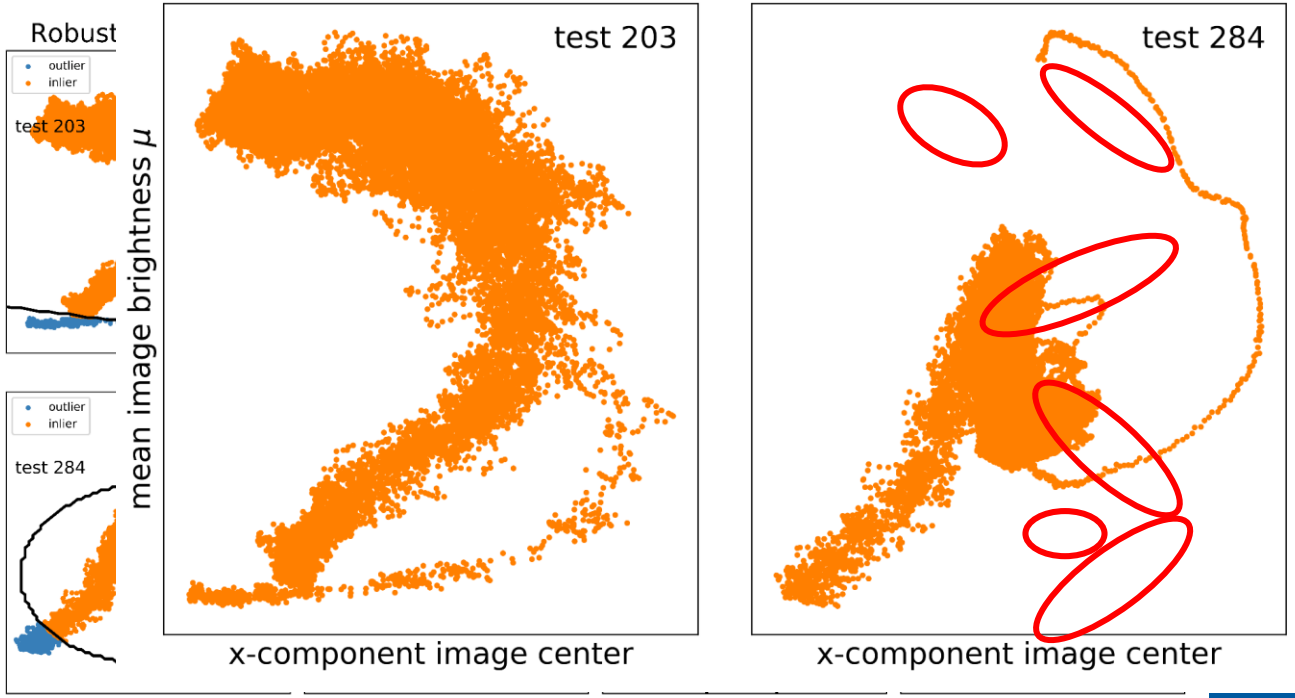
Anomaly detection

How to find an adequate algorithm for our applications?

Start: Comparison of two features $(\mu, \overline{x})_j$ for all $j = 1, \ldots, 30000$ images of test 203 and 284.

test 203

test 284



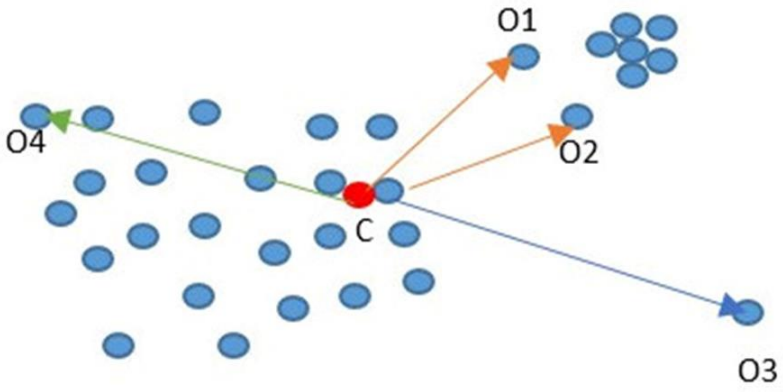
orizontal xis: orizontal osition of the age center

ertical axis: ean image rightness

Anomaly detection - Pros and Cons of Local Outlier Factor (LOF)

Advantages

- Algorithm recognizes local outliers
  ⇨ Applications: detect anomalies in different combustion flow phases and not in transition regime.
- Deals with regions of varying densities.
- Only requires a dissimilarity function not a distance function (i.e. triangle inequality is not required).

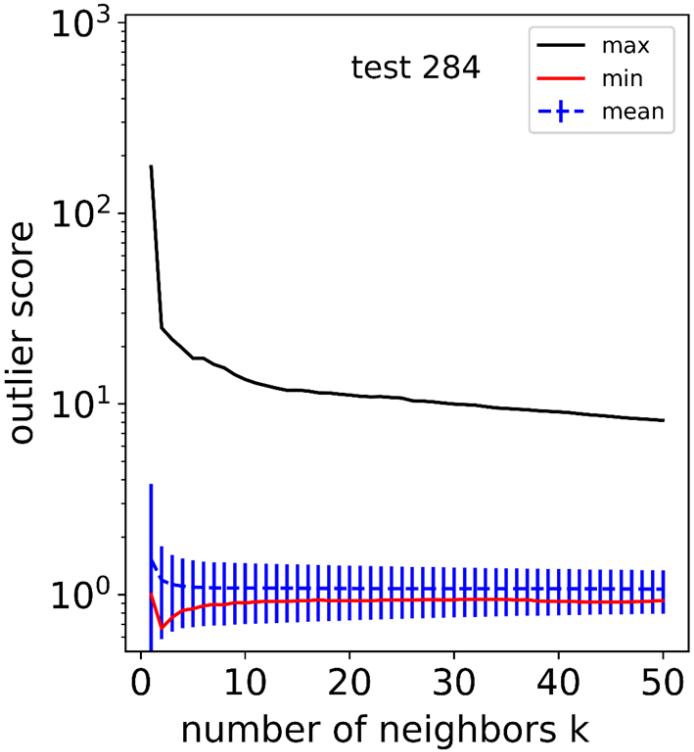


Disadvantages

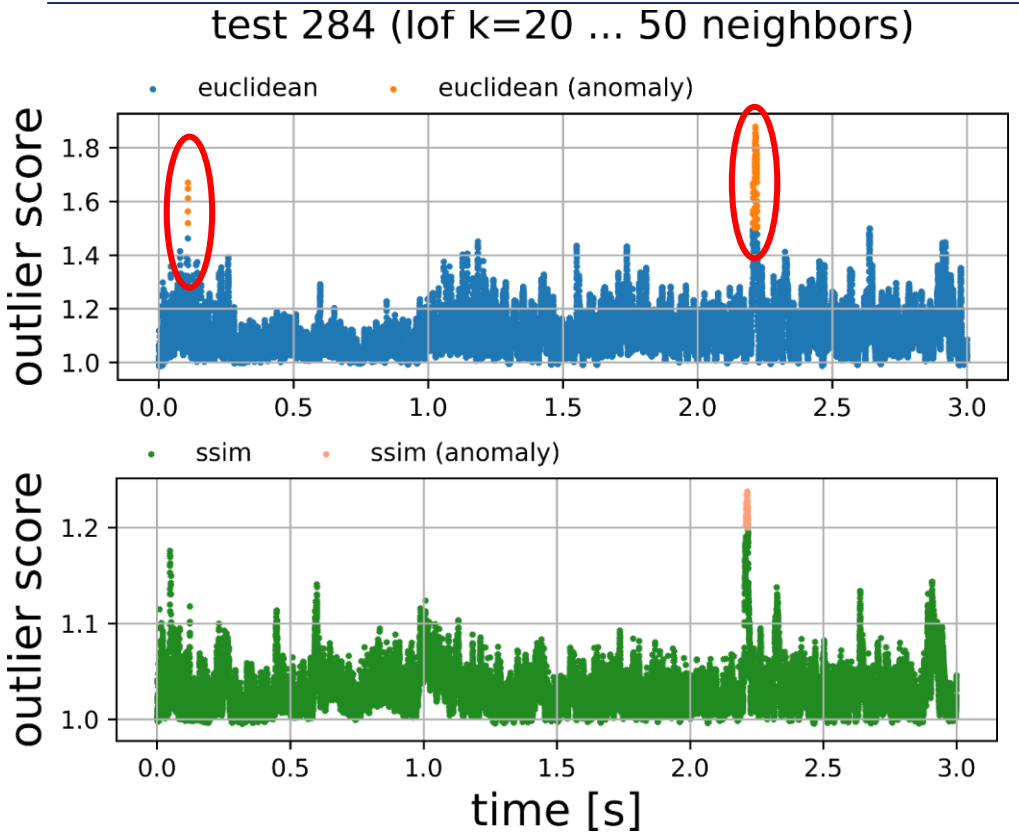
- Outlier score > 1.0 is hard to interpret (threshold value is problem dependent).
- No decision boundary (important for additional data).
- How to determine hyperparameter *k* (number of neighbors that is considered)?

Anomaly detection - How does the hyperparameter *k* affect the LOF result?

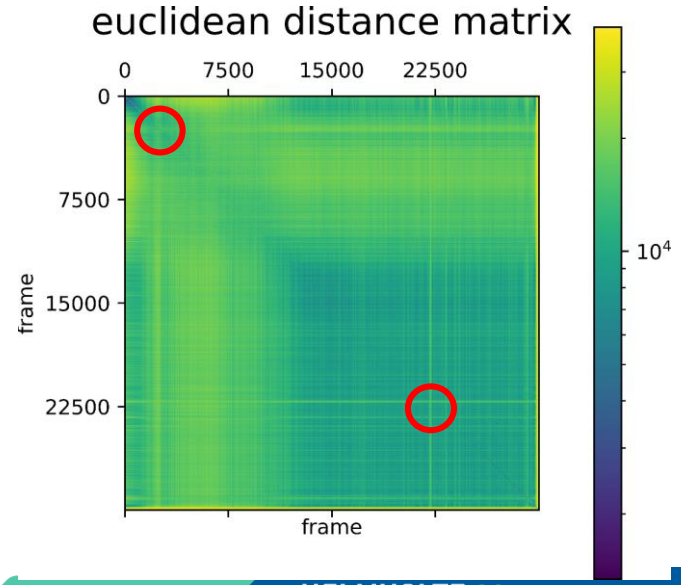
- If *k* is chosen too small, the result is affected by stochastic oscillations.
- If *k* is chosen too large, LOF becomes a global algorithm.
- In the literature, a lot of authors recommend *k*=20.
- Here: We compute LOF values for a range of different hyperparameter values, i.e. $\max_k\big(\text{LOF value (image } j\text{)}\big)$ pointwise for image $j = 1, \dots, 30000$ and $k \in \{k_{\min}, k_{\max}\}$.



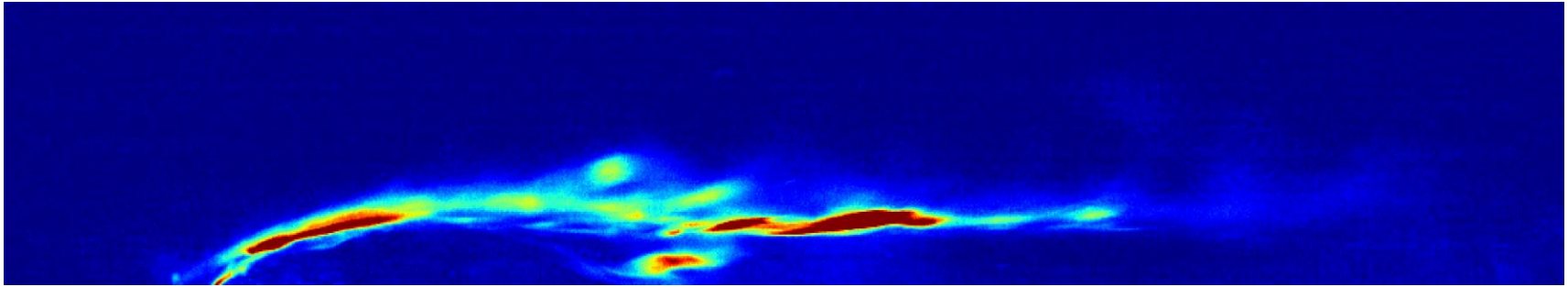
Anomaly detection - Test 284



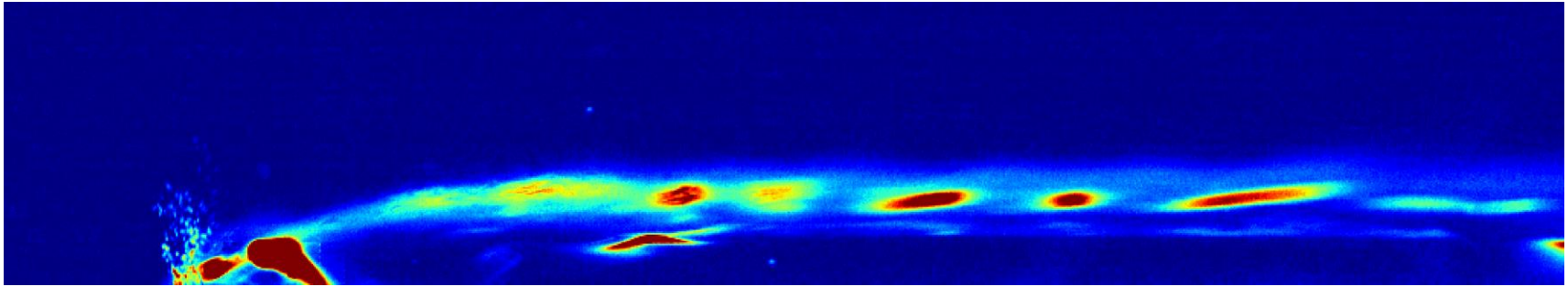
- Euclidean distance norm returns larger outlier score values (due to irregular matrix?).
- SSIM and Euclidean distance share some anomalies but there are differences.



Peak outliers of Euclidean metric (test 284)

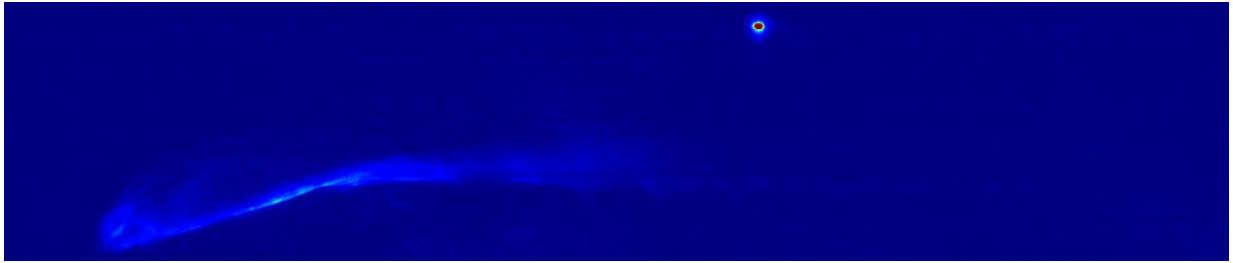


Flame fluctuations in ignition phase at t = 0.1078 s

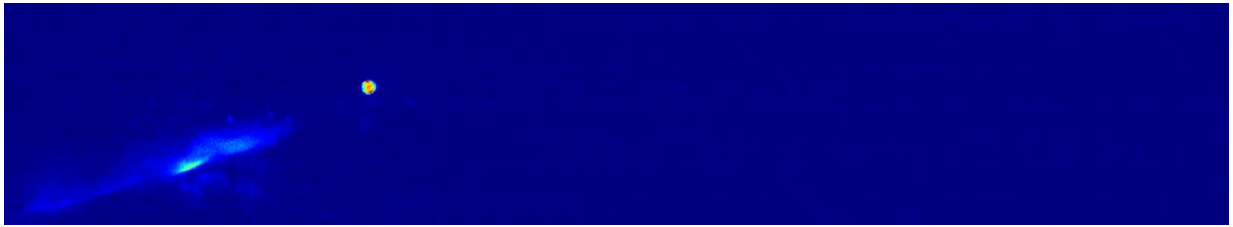


Droplet detection towards end of combustion at t = 2.2055 s

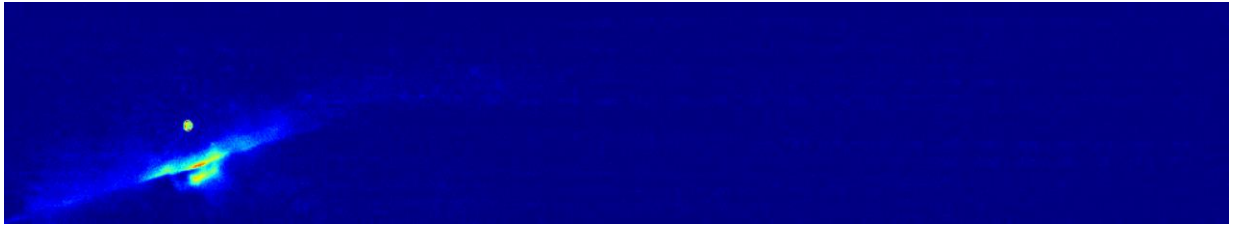
Some outliers found in other combustion tests



Test 291:
satellite droplet at t = 0.0253 s



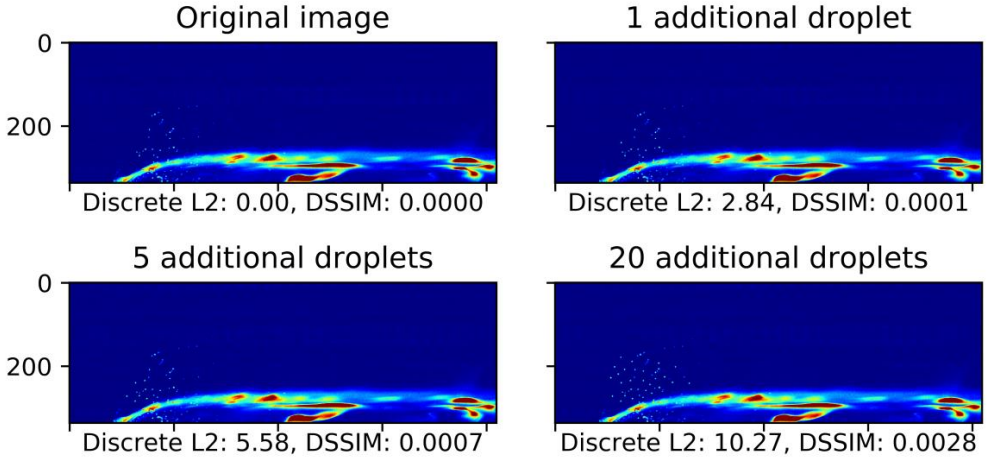
Test 296:
satellite droplet at t = 0.0017 s



Test 296:
satellite droplet at t = 0.0223 s

Conclusion and outlook

- Clustering and anomaly detection in rocket combustion image data is possible provided that distance measure is adequate.
- Further insights are possible if datasets are combined (e.g. anomaly detection in spectral and image data).
- Future work is spent on distance measures that are more adapted to the „interesting anomalies“.



Thank you for your attention!