Missing Image Detection in Melt Pool Monitoring

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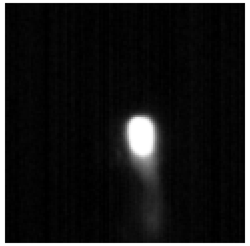
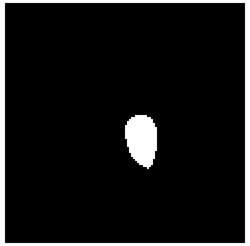
Contents

Exploratory Data Analysis

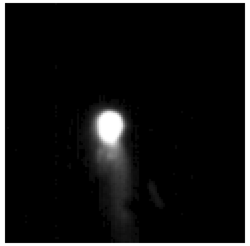
- Temporal evolution of the melt pool
- Elliptical globe with a tail of fumes
- Direction of fumes change continuously
- Bits fly off occasionally



Sample data



Sample data with filtering

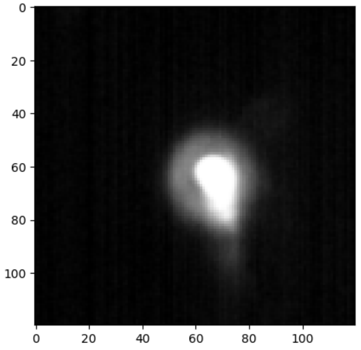


Part 2 data

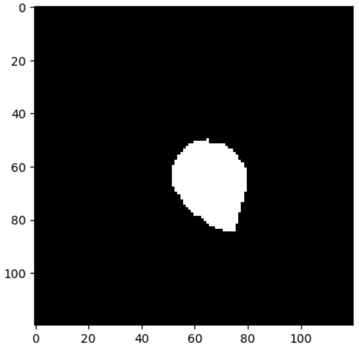
Image Thresholding

- Values of pixels below threshold, set to 0; above to 255
  - *lambda p: 255 if p > threshold, else 0*
- Reduces noise and decreases dimension
- Can remove artifacts
- Threshold value: hyper parameter for methods!

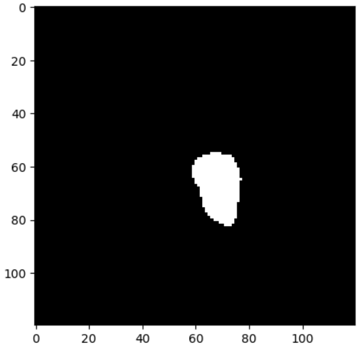
Original



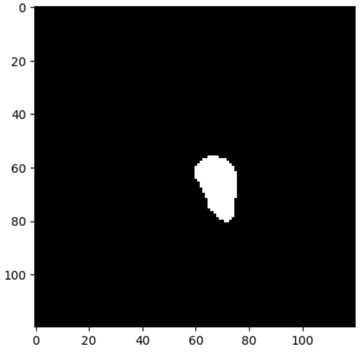
Threshold = 100



Threshold = 150

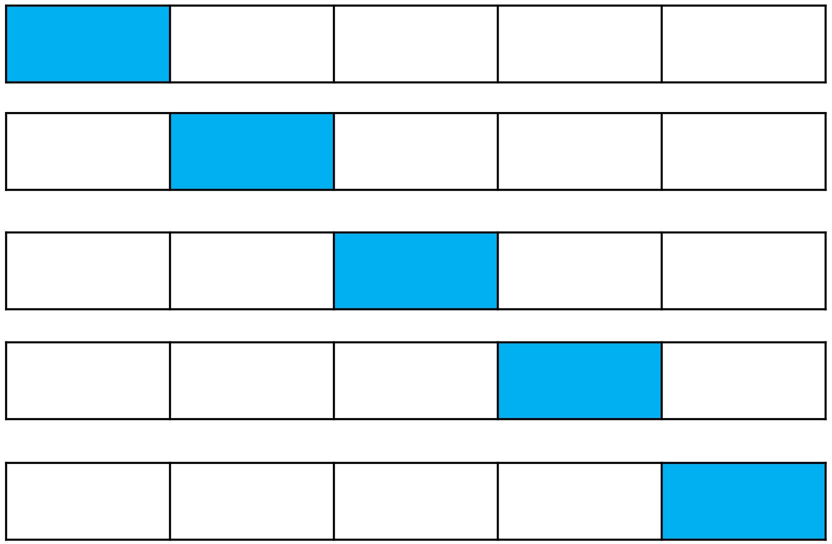


Threshold = 200

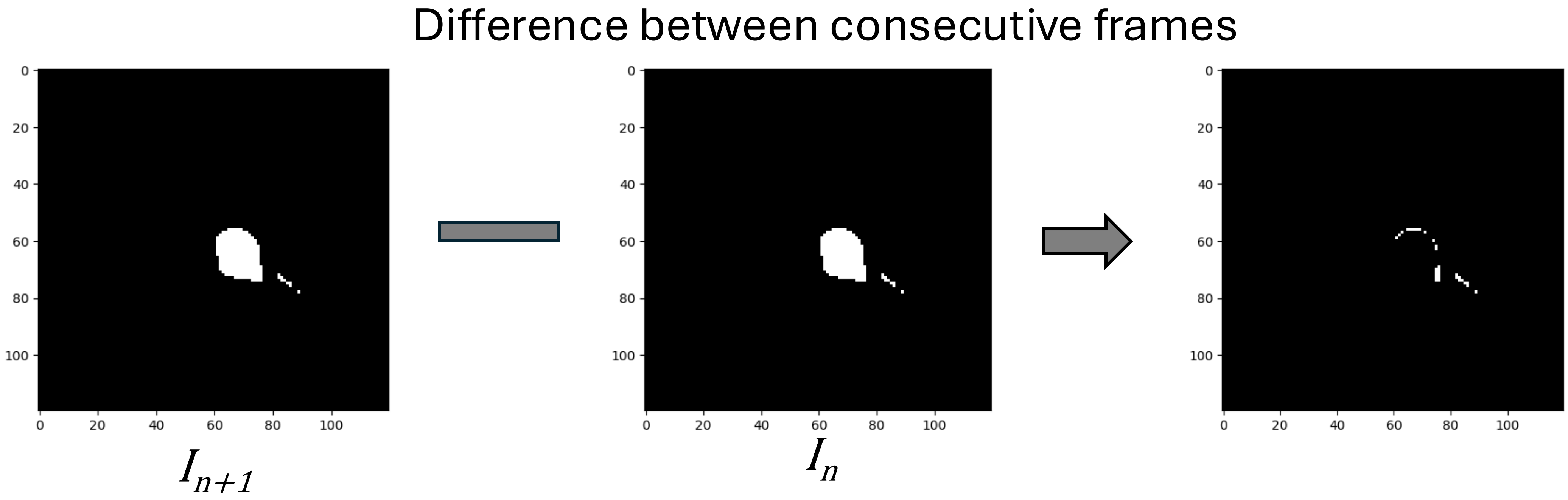


Dataset Generation

- Overall data pool (637 frames):
    - Sample data (437 frames)
    - Problem #1 data (first 200 frames)
- Testing and Validation Split: 2% holdout
- Five-fold Cross Validation
- Criteria #2 for scoring



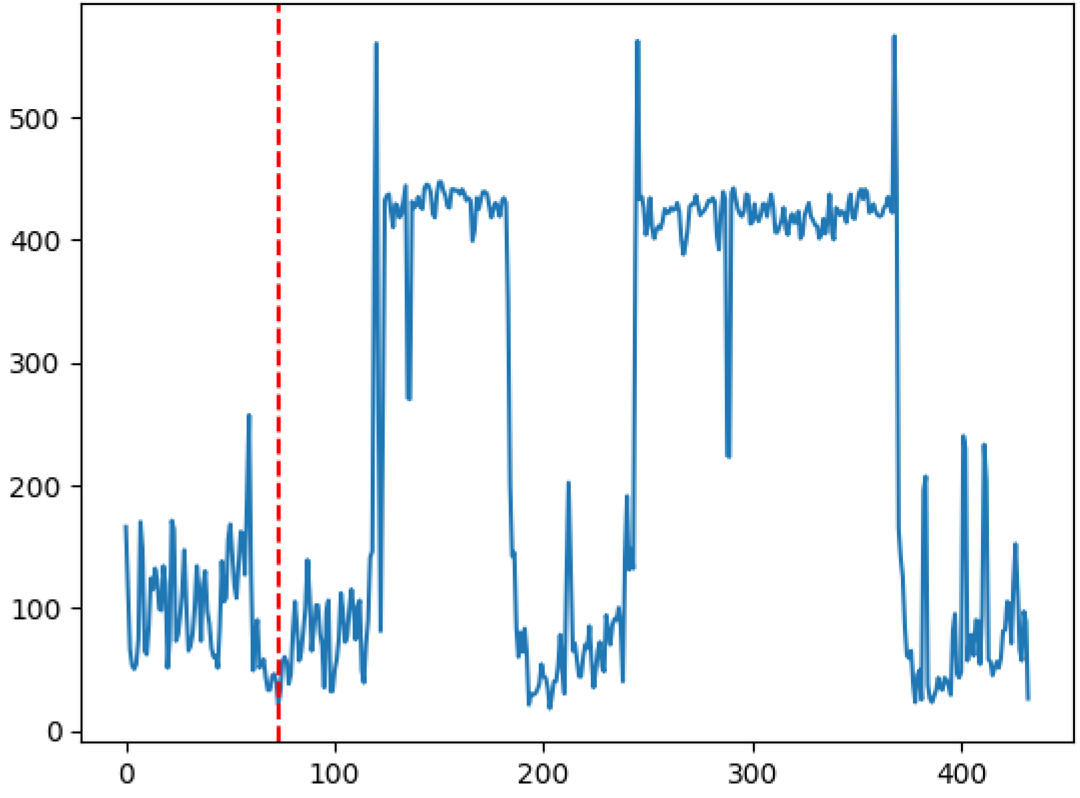
Difference between Frames



- Missing frame will only be marginally different from the previous frame

$$(I_{n+1} \cap I_n)'$$

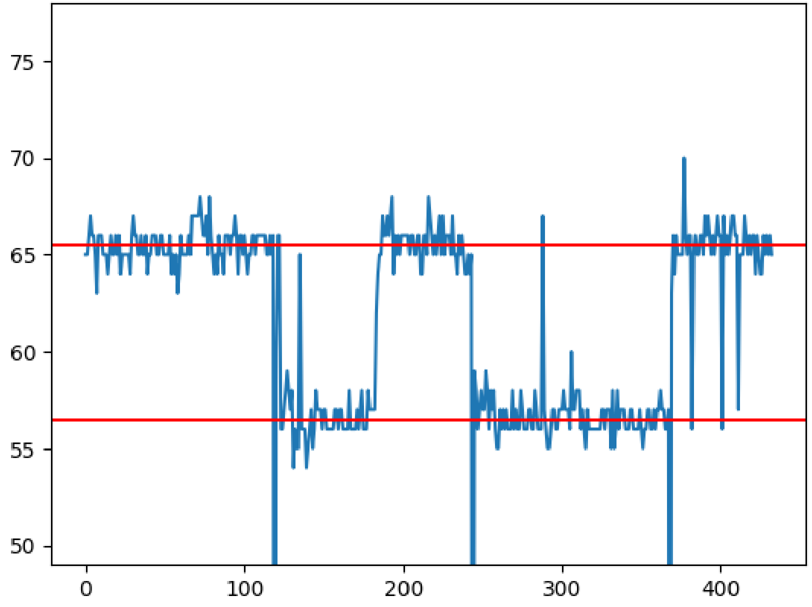
Comparative Difference Analysis



Missing frame 63 corresponds to minima

- Compute difference between missing frames and given frames
- Minimize area of the difference
- Area: Count of white pixels
- Direct difference: $I_n - I_x$
- Midpoint difference : $0.5(I_n + I_{n+1}) - I_x$
- Absolute difference: $|I_n - I_x| + |I_{n+1}|$

Center of Mass (COM)



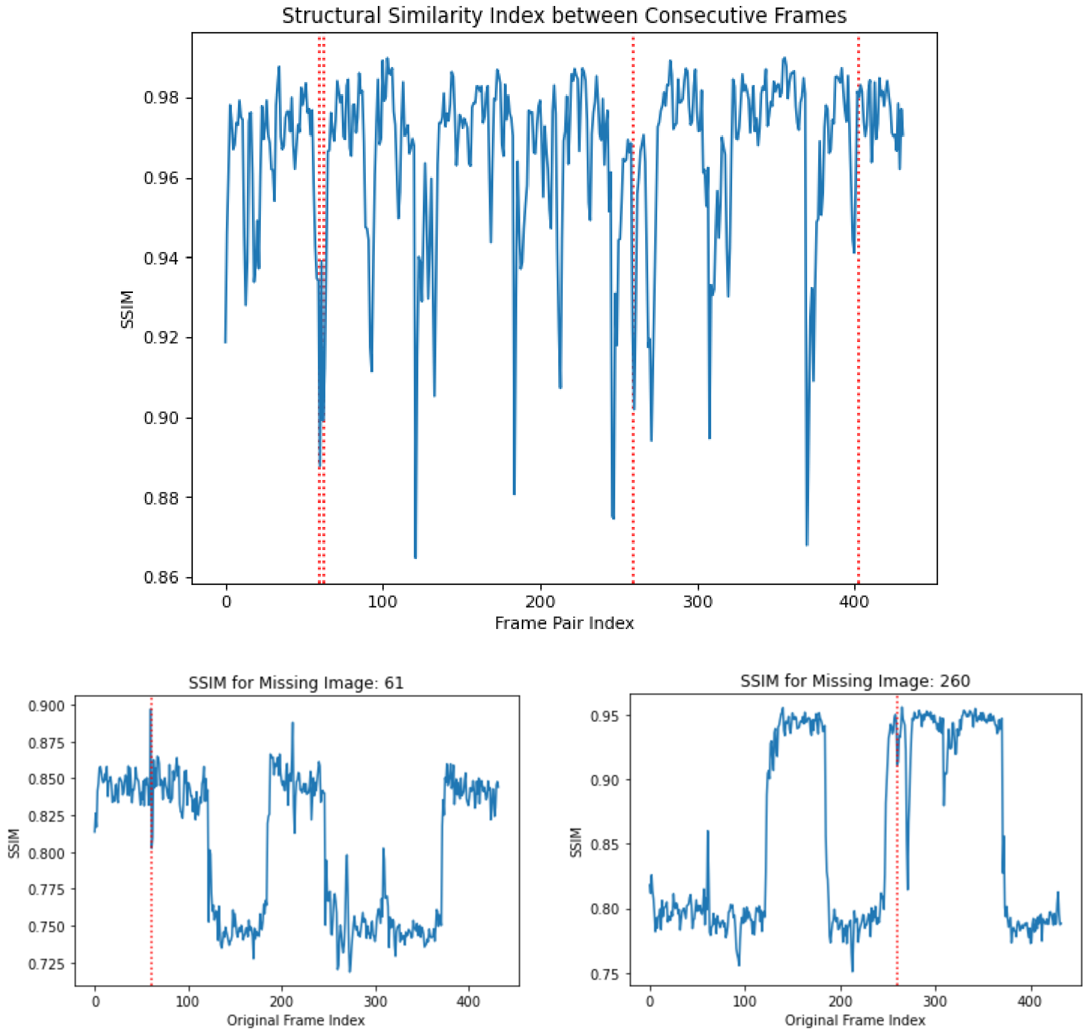
Evolution of y COM

- Oscillates between different positions
- Change is discrete; accompanied by tail flipping
- Label and partition the dataset based on COM position
- Measure COM of missing image and match to possible partitions

Similarity Comparison

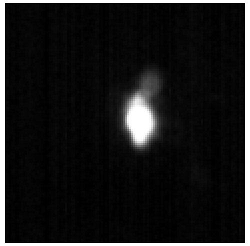
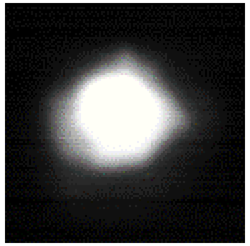
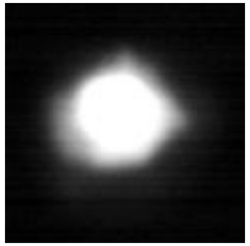
Metrics

- Hamming distance
- Area of white pixels
  - Count of white pixels
- SSIM (Structural Similarity Index Measure)
- PSNR (Peak Signal-to-Noise Ratio)
- NCC (Normalized cross correlation)

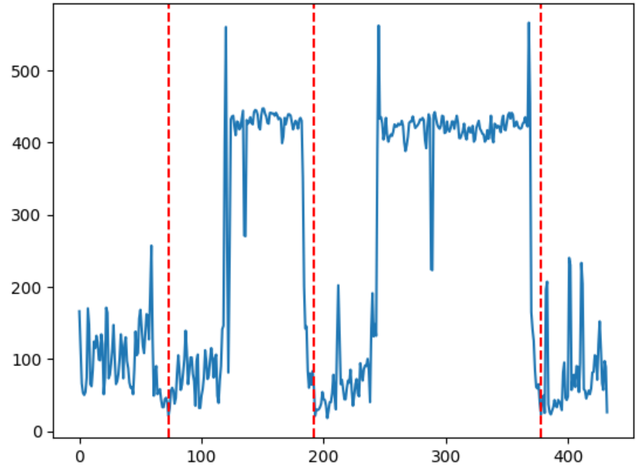


Challenges

- Outliers: Empty frames and super-bright frames

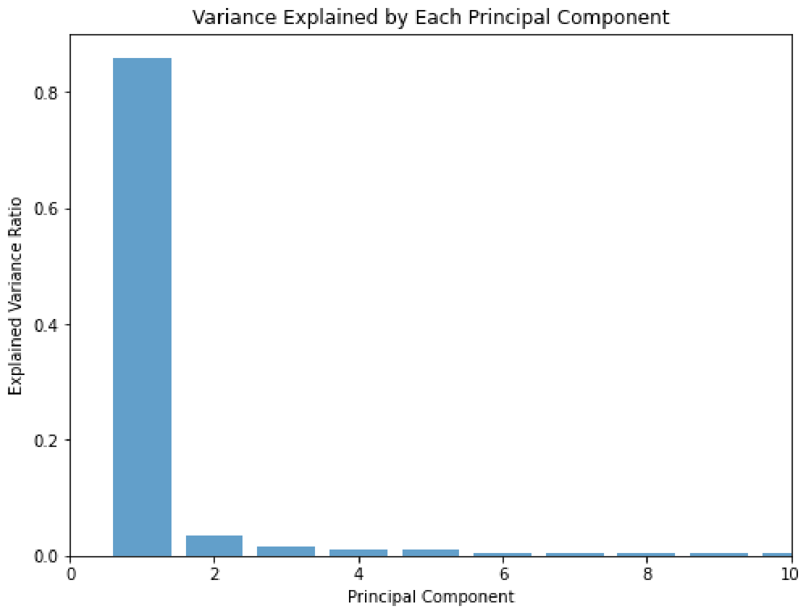
- Phenomenon is periodic; Missing frame can have multiple matches

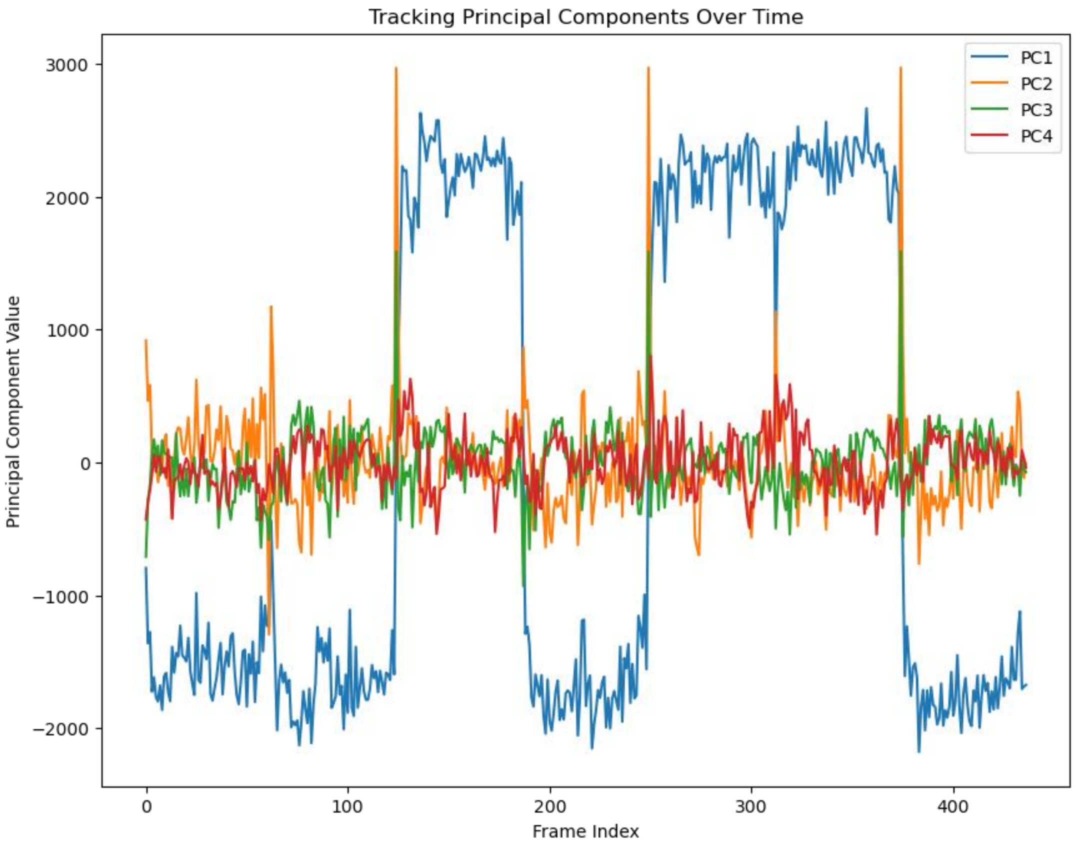


Principal Component Analysis

Principal Component Analysis (PCA) is applied to detect frame skipping and analyze the temporal evolution of the laser melt pool process.

- Flatten each image into a 1D array
- Sudden jumps or discontinuities in PC values may indicate frame skips
- Different PCs may capture various aspects of the melt pool dynamics



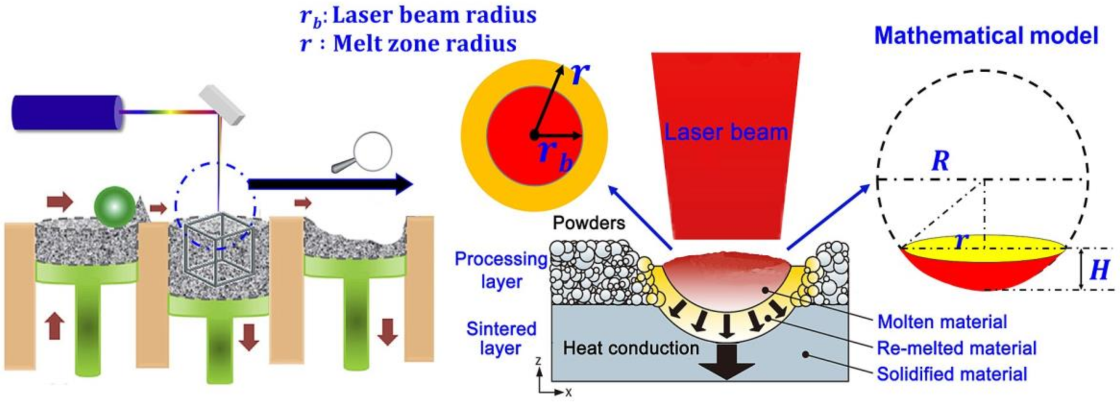


Results

Method		Average Score using Criteria #2
Random Sampling		17.5
Comparative Difference Analysis	Direct Difference	33.9
	Midpoint	**36.1**
	Absolute Difference	28.6
Similarity Analysis	Hamming Distance	23.8
	Area of White Pixels	24.6
	Structural Similarity Index Measure	21.4
	Peak Signal-to-Noise Ratio	27.7
	Normalized cross correlation	29.8
Principal Component Analysis		19.1

Problem 2: Approach #1

- **Observations:**
  - Melt pool can be abstracted as a circle and approximated to an ellipse when viewed by a camera
  - The plume can be abstracted as a parabola
- **Hypothesis:** frame skipping will result in abrupt morphing of melt pool and plume shapes and tracking them for consistency can help detect existence of missing frames.



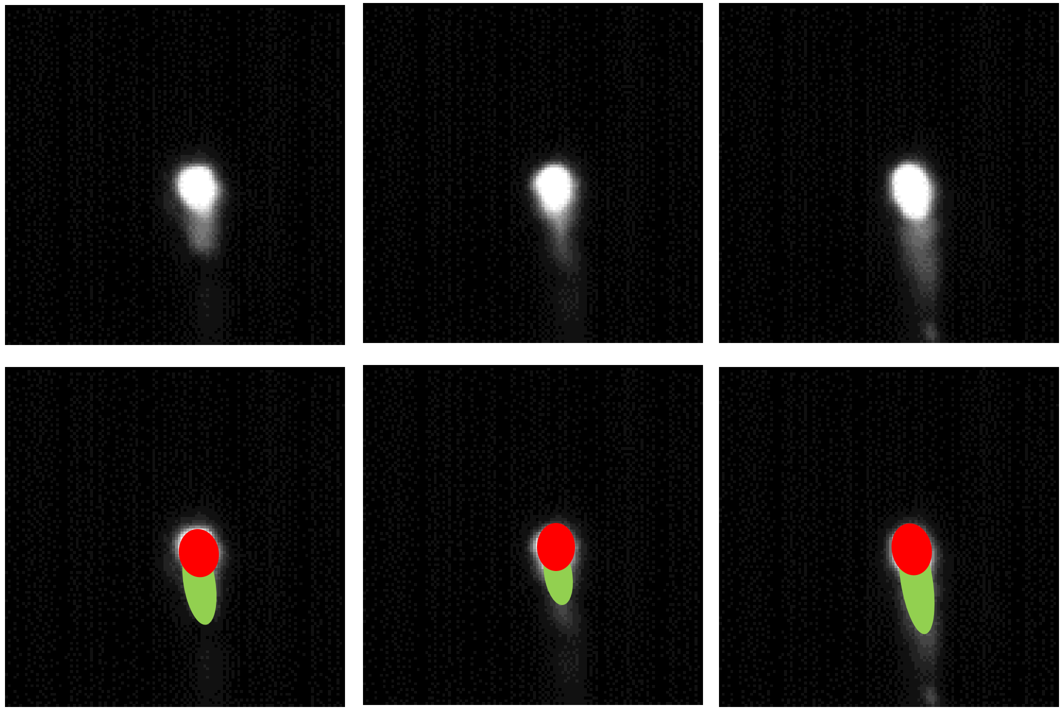
Schematic of selective laser melting and the heat transfer in molten pool. [1]

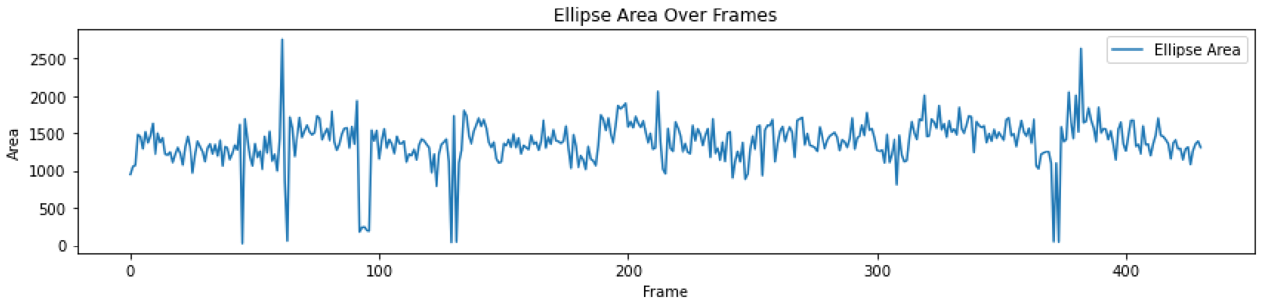
[1] Tan, C. *et al*. (2018) 'Selective laser melting of high-performance pure tungsten: parameter design, densification behavior and mechanical properties', *Science and Technology of Advanced Materials*, 19(1), pp. 370–380. doi: 10.1080/14686996.2018.1455154.

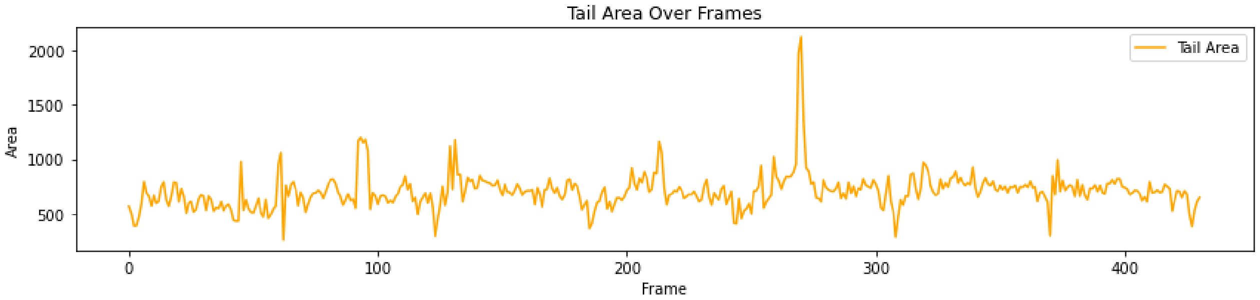
Melt Pool and Plume Tracking

Key steps:

1. Image preprocessing using binary thresholding
2. Contour detection using Suzuki-Abe algorithm [1]
3. Identification of optimal ellipse parameters using least square fitting
4. Visualization of area change



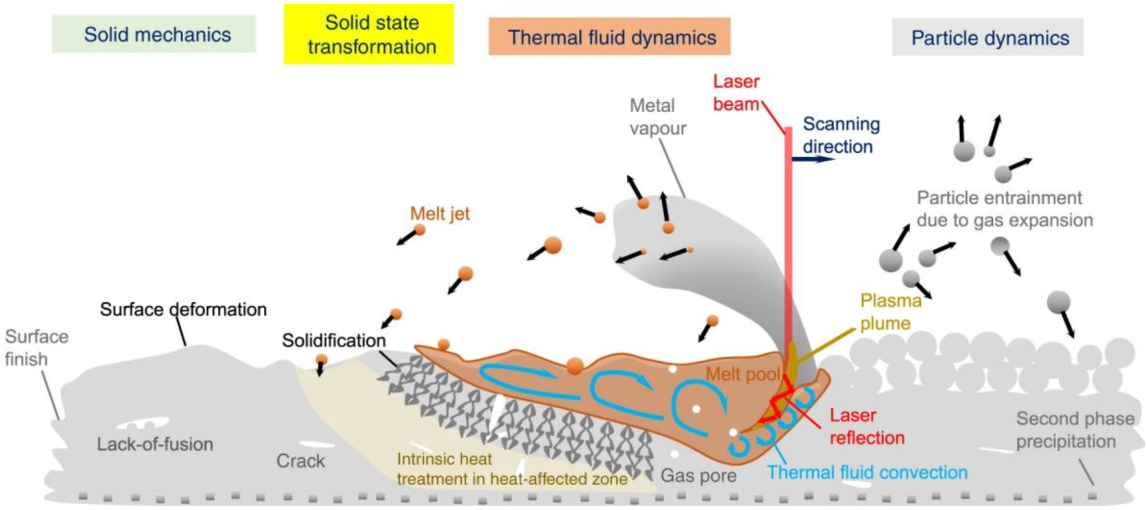




[1] Suzuki, Satoshi. "Topological structural analysis of digitized binary images by border following." *Computer vision, graphics, and image processing* 30.1 (1985): 32-46.

Problem 2: Approach #2

- **Observation:** several artefacts appear sometimes which travel from the plume towards the edge in the region of interest
- **Hypothesis:** frame skipping will result in abrupt changes in artefact position and tracking them can help detect existence of missing frames.



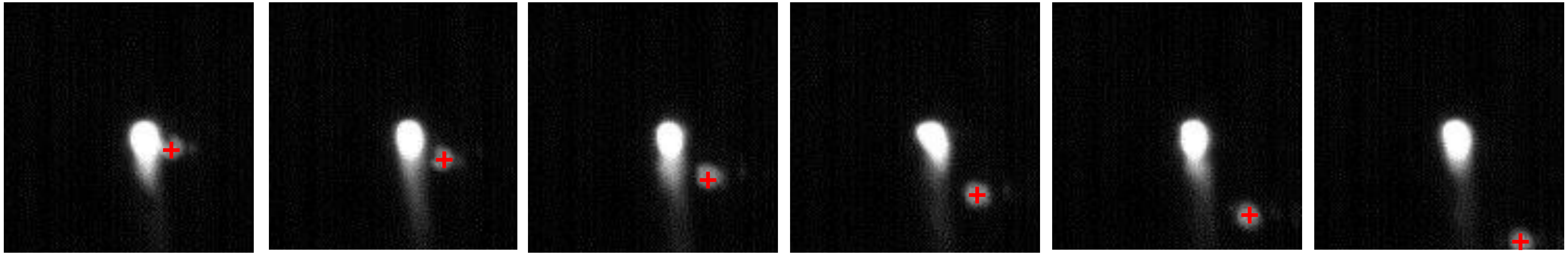
Schematic of artefacts generated in the process of selective laser melting. [1]

[1] Panwisawas C, Tang YT, Reed RC. Metal 3D printing as a disruptive technology for superalloys. *Nat Commun*. 2020 May 11;11(1):2327. doi: 10.1038/s41467-020-16188-7. PMID: 32393778; PMCID: PMC7214413.

Artefact Detection and Tracking

Key steps:

1. Preprocessing using binary thresholding
2. Region of Interest (ROI) creation excludes main melt pool and plume areas
3. Contour detection in ROI using Suzuki-Abe algorithm
4. Artifact candidate filtering based on size and shape eliminates noise and non-artifact objects
5. Temporal tracking for frame skip detection



Results

Method	Average Score using Criteria #2
Random Sampling	17.5
Principal Component Analysis	19.1
Melt Pool and Plume Tracking	20.6
Artefact Detection and Tracking	18.3
Melt Pool, Plume and Artefact Tracking	**24.8**

Conclusion

- Explored multiple approaches for detecting missing images in melt pool monitoring
  - Simple difference-based methods outperformed more complex similarity measures for problem 1
  - Combination of Melt Pool, Plume, and Artefact Tracking is the best performing method for problem 2
- Limited dataset size may impact generalizability
- Given more time:
  - Adaptive thresholding for varying lighting conditions
  - Synthetic data generation using multi-physics simulation

Thank You

Questions?