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Abstract

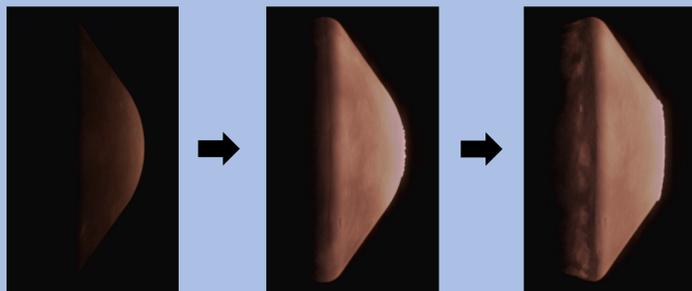
Arcjets are plasma wind tunnels used to test the performance of heatshield materials for spacecraft atmospheric entry. These facilities present an extremely harsh flow environment with heat fluxes up to 10^9 W/m² for up to 30 minutes. The plasma is low-temperature (~1 eV) but high pressure (> 10 kPa) creating high-enthalpy supersonic flows similar to atmospheric entry conditions. Typically, material samples are measured before and after a test to characterize the total recession. However, this does not capture time-dependent effects such as material expansion and non-linear recession. This work will present new analysis of arcjet test videos which measure both the time-dependent 2D recession of the material samples and the shock standoff distance. The results show non-linear time-dependent effects are present for some conditions. The material and shock edges are extracted from the videos by training and applying a convolutional neural network. Due to the consistent camera settings, the machine learning model achieves high accuracy (± 2 px) relative to manually segmented images with only a small number of training frames (80).

Motivation

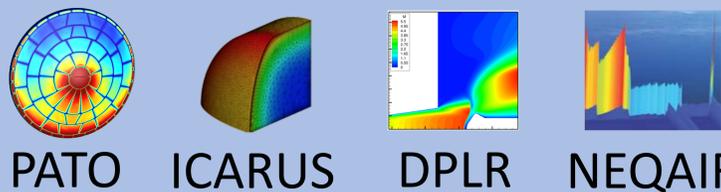
Video footage of arcjet tests represents an untapped data resource with submillimeter (~0.1 mm) resolution. Machine learning segmentation of these videos can provide:

1. Time-resolved material recession/shape

Identify time-dependent processes: (swelling, shrinkage, different layer recession rates, shape change, etc.)



2. Verification & validation for coupled aerothermal, material, &/or radiation codes



3. Automated & standardized video processing for increased data throughput

Acknowledgements

This work was conducted with support from the NASA Ames Center Innovation Fund and the NASA Science Mission Directorate (PICA Sustainability and MSR EEV projects). The authors would like to acknowledge useful conversations with Federico Semeraro and Mairead Stackpoole.

References

- [1] F. S. Milos, Y. Chen, and M. Mahzari, *Arcjet Tests and Thermal Response Analysis for Dual-Layer Woven Carbon Phenolic*, Journal of Spacecraft and Rockets 2018 55:3, 712-722
- [2] Ronneberger, O., Fischer, P., and Brox, T., *U-Net: Convolutional Networks for Biomedical Image Segmentation*, arXiv e-prints, 2015.

Summary

Automated segmentation of arcjet videos provides a new tool for tracking the time-dependent position of material & shock surfaces at sub-millimeter precision. Results show that material recession, shock-standoff and sample shape can all change with time. Future work will focus on using these high-fidelity measurements to validate coupled aerothermal, radiation, and/or material simulations.

Machine Learning Model

Convolutional neural networks (CNNs) are now the go-to tool for image segmentation. For this project, a CNN was developed to segment a variety of arcjet test videos with different model shapes, colors and camera settings.

Architecture



The neural net is constructed using the Keras Python API with TensorFlow as the backend. The encoder architecture uses pairs of convolutional layers with 0.2 dropout at each of two down-sampling stages. The decoder has symmetric up-sampling stages. Since the network is fully convolutional, it can segment any video frame size.

This design was chosen because it was the minimal network required to produce good segmentation, it could be trained quickly, and it required fewer training images than other architectures.

Training

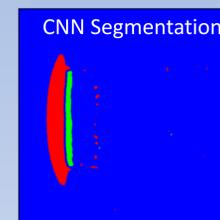
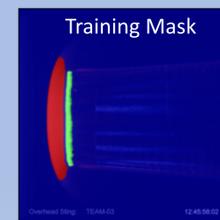
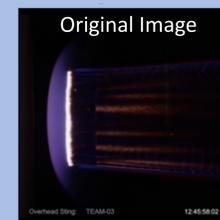
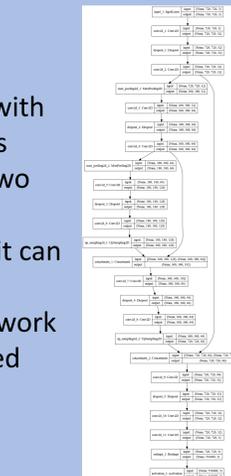
The training data set was constructed from 8 representative frames from each of 10 videos. Each training frame was manually segmented. These 80 frames and associated masks were then broken down into 128x128 sub-images. This tiling allowed the network to be trained on a variety of video frame sizes and to be trained on a personal laptop. This training set of 5000 sub-images was then further expanded using geometric data augmentations, for an effective training set of 40,000+ image patches.

The augmented data set was split into training (75%), validation (20%), and test (5%) portions. Due to the consistent framing of the images, the validation and test performance was nearly identical to that of the training set. Most of the loss occurs with low lighting edge cases

The resulting segmentation was sufficient to capture the leading edge of most video frames and the network performs sufficiently well to automate the processing of all tested videos.

Validation Performance Metrics

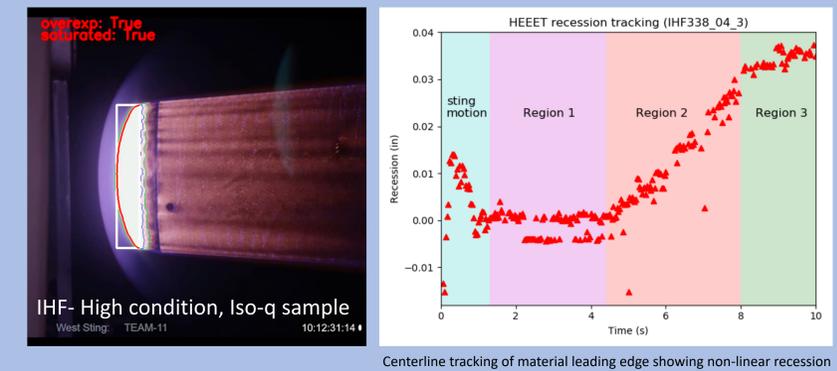
Class	Precision	Recall	F1	Accuracy
Model	0.96	0.82	0.88	0.97
Shock	0.91	0.92	0.92	0.97
Background	0.91	0.99	0.98	0.96



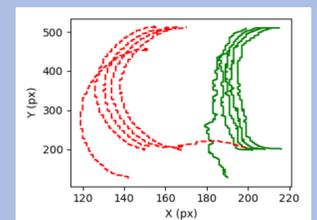
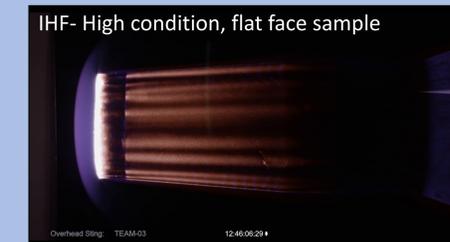
Results: non-linear recession

Automated analysis of every frame in arcjet test videos has revealed certain samples with non-linear recession. The test shown below of the new HEEET material shows at least three distinct recession rates in a constant aerothermal environment. After the sting arm stabilizes, the first couple seconds show little to no recession. The second region has a nearly constant recession rate, and the third region exhibits a markedly reduced recession rate.

These data indicate a need for material models which can account for non-linear effects such as material swelling and shrinkage.



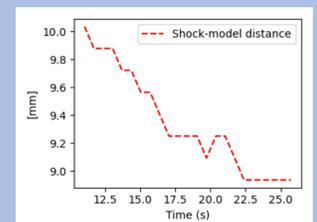
Results: shock standoff



Leading edges of shock (red) and sample (green) plotted over the test timeframe

Since the segmentation also captures the shock front, it is simple to measure the shock-sample distance. This standoff distance is typically constant in time and could provide a validation metric for coupled aerothermal + radiation simulations (e.g. DPLR + NEQAIR).

However, certain samples show a marked time dependence of the standoff distance. This decreasing shock-sample distance implies that the pressure at the sample surface is changing with time. This means either the aerothermal conditions of the arcjet are changing or more likely, that the sample is becoming more porous and there is increasing flow into the surface.



Plot of shock standoff distance over time. For comparison, the total material recession is 2mm

Results: shape change

The segmentation results can also resolve the changing shape of different samples. The plots to the right show initial and final contours for a PICA-NuSil sample (images from motivation section) from a test in the HyMETS arcjet. The high-fidelity segmentation of the images (0.1 mm resolution) indicate the presence of several effects:

- The sample shape deforms/flattens at the nose and develops mm scale ripples/bubbles
- The entire sample is expanding (e.g. negative recession at the edges).

This high-fidelity shape data can provide validation for the newest 2-3D HPC material simulations.

