National Aeronautics and Space Administration

Segmentation of Lightweight Ablator Micro-Tomography Using Deep Learning

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Overview

Ablative thermal protection systems (TPS) are essential for high speed entry of planetary atmospheres, such as those of Earth and Mars. Upon entry the kinetic energy of the spacecraft is converted into thermal energy, leading to high heat fluxes at the wall of the craft. Because of this extreme heating, a robust ablative TPS material must be selected. A common material selection today is phenolic-impregnated carbon ablator (PICA), which is a low-density carbon material known for producing dust that is not suitable to a cleanroom environment. To mitigate dust created by a PICA heatshield, a silicone-based spray called NuSil is applied to the surface of the TPS, creating PICA-NuSil (PICA-N). PICA-N has been observed to have a different material response from regular PICA during high enthalpy flow testing, producing surface temperatures up to 200 K less than those seen for PICA [1]. To better understand this phenomenon, it is critical that robust methods of PICA-N material characterization are developed. The purpose of this project is to investigate Object Research Systems' (ORS) Dragonfly deep learning tools as a means of accurately segmenting and characterizing PICA-N. Systematic testing of this software has shown that Dragonfly deep learning tools have strong potential for accurate segmentation/characterization of PICA-N and other TPS materials.

Objectives

- Test Dragonfly deep learning as a method of segmentation and characterization of TPS materials
- Develop and validate deep learning models to segment FiberForm®, PICA, and PICA-N using Dragonfly deep learning

Dragonfly Deep Learning

ORS Dragonfly utilizes a variety of convolutional neural networks to simulate the human brain's ability to recognize patterns. Like the brain, the neural network strengthens and weakens connections between neurons using weighted values. By iteratively comparing the output of the network to labeled training data, the machine "learns" what weighted values produce correct results.

A neural network is often composed of many hidden layers, each layer focusing on a different aspect of the image. Dragonfly utilizes Google's Tensor flow and Keras to develop these neural networks to segment, denoise, and enhance the resolution of micro CT image data [2].

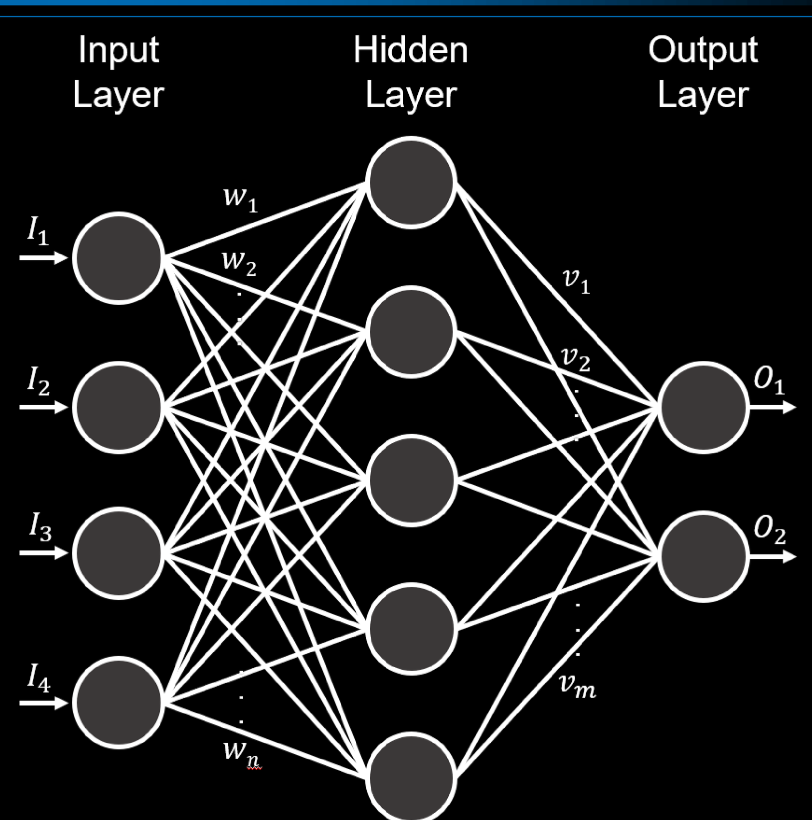

Figure 1: Example of a simple multilayer artificial neural network. Outputs (O_1, O_2) are compared to labeled training data to iteratively determine weight values (w, v).

Results

FiberForm® Segmentation

FiberForm® deep learning models were trained to 99.9% accuracy with very few complications. Models had no issue distinguishing between void and fiber and were not misled by the presence of noise or image artifacts.

Segmentation of FiberForm® showed a porosity (i.e. void fraction) of 86%. FiberForm® has an average porosity of 86.9% [3], showing that segmented data is well within the acceptable porosity variation of the material.

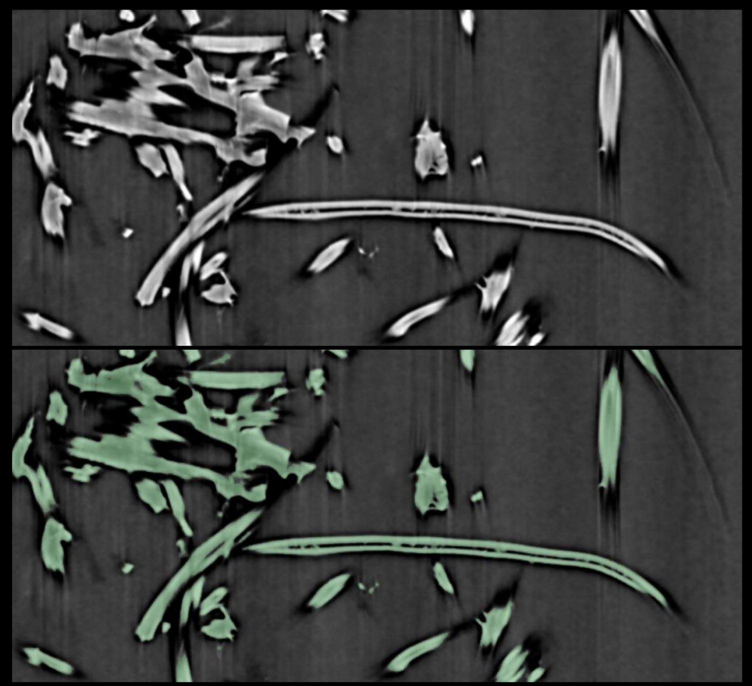

Figure 2: Segmented FiberForm® using a U-Net deep learning architecture

PICA & PICA-N Segmentation

Models of PICA and PICA-N (Figure 3) were trained to ~97% accuracy and were capable of distinguishing resin and NuSil from Fiber while ignoring noise and image artifacts. Available PICA-N data showed no distinction between resin and NuSil; therefore both were grouped as one material.

PICA segmentation showed a percent resin volume of 20%, which is 10% higher than anticipated; however, an overestimate was expected, as micro-pores in the resin were not properly captured in the available PICA data. PICA-N segmentation of two data sets resulted in an average percent resin volume of 22% but could not be verified due to lack of validation data.

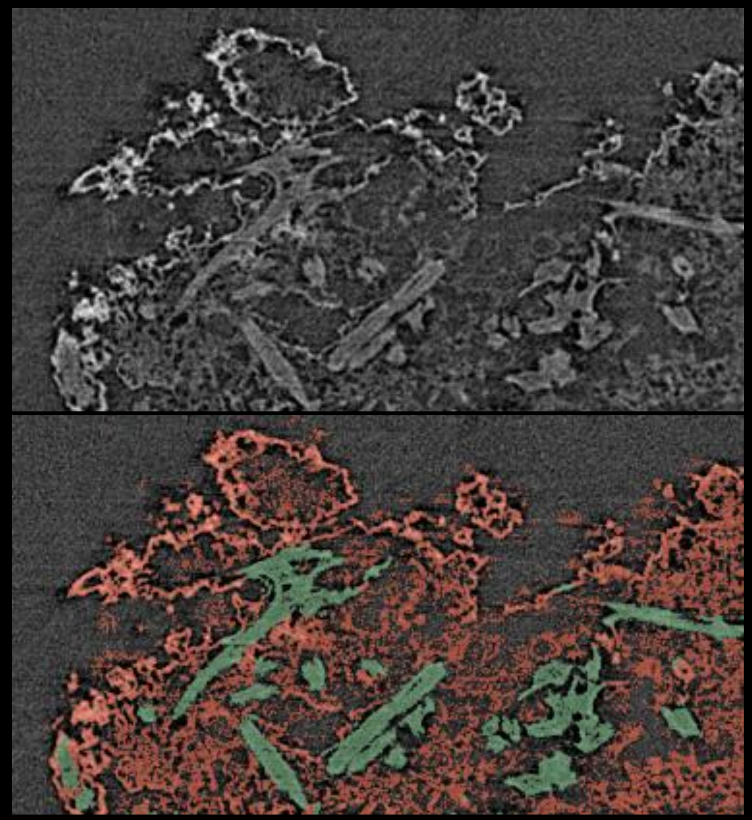

Figure 3: Segmented PICA-N using a Sensor 3D deep learning architecture

Conclusions

Accurate segmentation of FiberForm®, PICA, and PICA-N was achieved using ORS Dragonfly deep learning tools. Both FiberForm® and PICA models were validated, with an expected overestimate of PICA resin volume. Future work is required in order to validate PICA-N segmentation models, as validation data is not presently available. Additionally, future imaging of phenolic resin on a smaller scale may offer better insights into micro-porosity of PICA resin. Equipped with a user-friendly GUI, ORS Dragonfly deep learning tools are simple to learn and require little foreknowledge of machine learning. In all, these tools offer a powerful solution to the problem of TPS material segmentation and characterization.

Ablative TPS

During entry of a planetary atmosphere, heating of the TPS will cause phenolic resin to pyrolyze, ejecting gases into the boundary layer and transpirationally cooling the leading edge of the capsule. Additionally, heat is carried away from the craft as the layer of charred fiber is removed through sublimation and spallation. PICA (Figure 4) is one of the most advanced modern ablative TPS materials, being a low-density solution and offering exceptional ablation performance. [4]

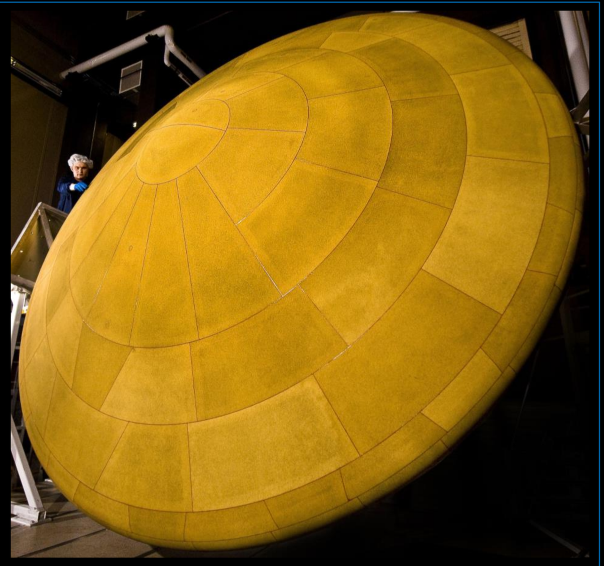

Figure 4: Mars Science Laboratory PICA based heat shield [5]

FiberForm® (Figure 5) is a fibrous carbon insulation designed by Fiber Materials Inc. for vacuum and high temperature applications. This material is extremely porous and inhomogeneous, leading to property variations at the microscale. When FiberForm® is impregnated with phenolic resin, it becomes PICA, and acts as the structural backbone of the TPS material.

Figure 5: Microstructure of FiberForm®

References & Acknowledgements

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Thank you to Dr. Brody Bessire, Dr. Arnaud Borner, and Dr. Francesco Panerai for their support and guidance throughout this project. Also, a special thanks to Collin Foster, who provided knowledge and resources on deep learning and data manipulation.

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