Analysis of Bi-2212 Superconducting Filament Structure Using Machine Learning Algorithms

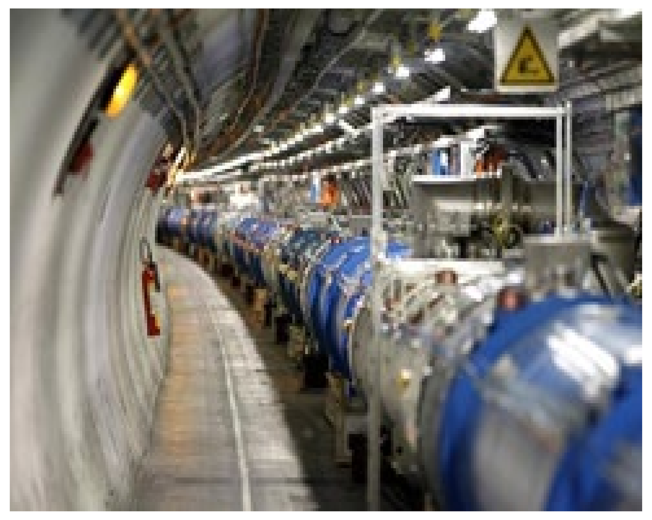
Priyanka Fnu[1], Je-Yu (Leo) Chou[2], Fletcher A. Theisen[3], Reed R. Oberg[4], Matthew C. Jewell[3]

[1]Department of Computer Science – University of Wisconsin - Eau Claire, [2]Department of Computer and Data Science – Case Western Reserve University
[3]Department of Material Science and Biomedical Engineering – University of Wisconsin-Eau Claire, [4]Department of Physics and Astronomy – University of Wisconsin-Eau Claire

Introduction

What are we studying?

- Superconductors are a class of material that can conduct electricity with zero resistance when chilled to temperatures below their unique critical temperature.
- Due to the lack of resistance, large electrical currents can be placed through superconductors, which create strong magnetic fields that can be used in particle accelerators, medical imaging devices, and nuclear fusion reactors.



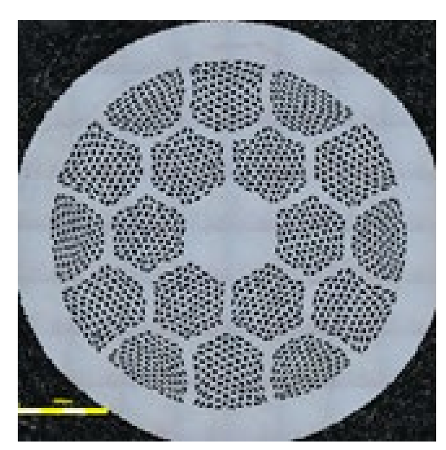
The superconducting magnets of the Large Hadron Collider at CERN in Geneva, Switzerland

Why are we studying it?

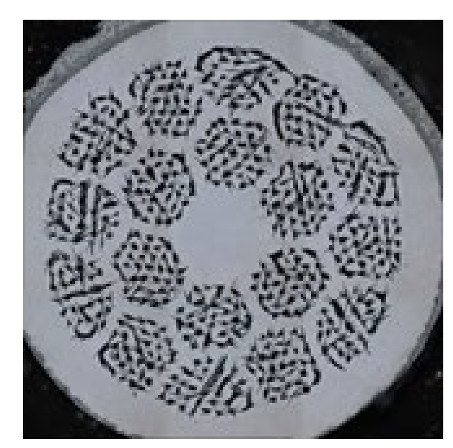
- The agglomeration of Bi-2212 filaments during the heat treatment process has been shown to reduce the performance of the wire overall.
- Classifying and categorizing the filament structure of Bi-2212 after the heat treatment process creates is an important step in accessing the quality of Bi-2212 wires in production.

Bi2212 Wire

- $Bi_2Sr_2CaCu_2O_8$ (Bi-2212) is a high temperature superconductor wire manufactured using the powder-in-tube method to create a standard round-wire shape.
- Then, the wires are given a heat treatment to crystallize the Bi-2212 powder, and it is after this treatment that the filament structure emerges from agglomeration of the filaments as the Bi-2212 cools and crystallizes.
- **The level of agglomeration is important because it lowers the current density and increases AC losses in the wire, which in turn negatively impacts the wire performance in a magnet.**



Before heat treatment



After heat treatment

Applying Machine Learning Models

Motivation

Manually labeling Bi-2212 filaments is slow and tedious. To automate this, we used deep learning models: U-net for initial segmentation, and SAC-Net for improved accuracy. SAC-net captures fine edges and multi-scale context, making it effective for detecting both single and conjoint filaments in complex bundles.

U-net

Why U-net?

- Well-established and widely used for medical and scientific image segmentation
- Works effectively with small datasets
- Encoder-decoder structure captures both global context and local details
- Skip connections help preserve fine boundaries
- Fast to train and implement

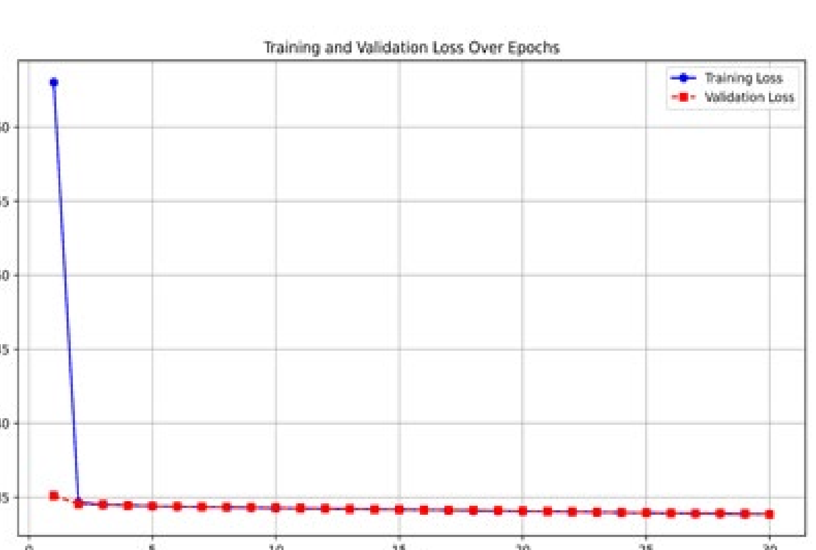
Sac-net

Why Sac-net?

- Specifically designed for thin, overlapping, and complex structures (like Bi-2212 filaments)
- **Multi-scale feature extraction** to improve global attention.
- **Edge-Preserving Modules** enhance boundary accuracy
- **Interpolation + Convolution** avoids artifacts from transposed convolutions
- **Auxiliary outputs** improve training stability and segmentation accuracy

Comparison

- **U-net** is effective for our task, capturing full filament regions, including both single and conjoint filaments, with strong pixel-wise accuracy.
- **SAC-net** highlights fine edges well but struggles to segment complete filaments—showing that edge-focused architectures may not fit our needs. Also, Sac-net seems to have a very high rate of convergence and similar validation/training loss.

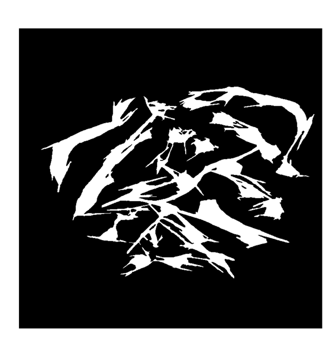


Sac-Net

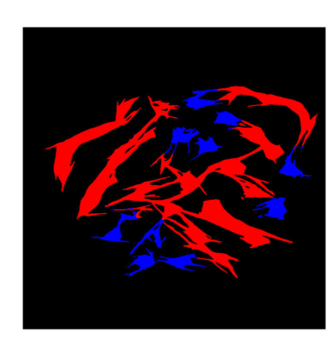
U-Net

U-net

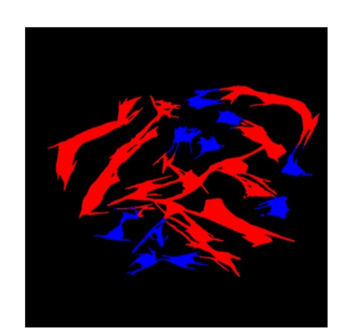
Overall Accuracy : 95%
Conjoint Filament accuracy – 75%
Isolated Filament accuracy – 71.3%



Threshold



Model Prediction

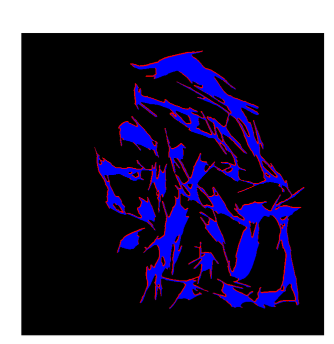


Labeled Ground Truth

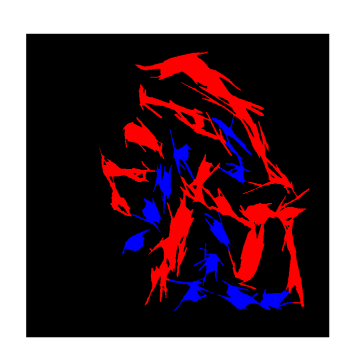
Sac-net

Overall Accuracy : 93.7%
Conjoint Filament accuracy – 59.4%
Isolated Filament accuracy – 3.19%

Threshold



Model Prediction



Labeled Ground Truth

Progress

- **U-net achieved 95% overall accuracy, and about 73% accuracy when just focusing on filaments, without the background.**
- **Sac-net has an overall accuracy of 93.7% and about 31.3% accuracy of filaments as it's detecting edges not the conjoint and isolated classes.**
- **We reexamine the current Sac-net architecture and determine whether the edge preserving module is dominating the model. We will continue to add images to our training datasets so that the models can be even more robust.**
- **We would like to find a way to create an executable file to avoid any interaction with code, however, the version of TensorFlow may cause some issues.**

Acknowledgements

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