

# FibriPy: a software environment for fiber analysis from 3D micro-computed tomography data

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## ABSTRACT

Analyzing digital images containing fibrillar structures is important across many science domains, from cytoskeleton detection in biology to filament detection in materials science. This paper introduces **FibriPy**, a software tool that enables accurate fiber detection from 3D imagery. We provide examples using micro-computed tomography ( $\mu$ -CT), an imaging technique used for inspection of new materials samples. Our results show that **FibriPy** can be used for quality control of materials in the manufacturing processes.

**Keywords:** quality control, object recognition, machine learning, 3D imaging

## 1 Introduction

Imaging facilities, such as those using X-ray synchrotron radiation (MacDowell et al. 2012) produce large rates of data, much of it as 2D and 3D images. Many scientists depend upon extracting sample structure and features from these high-resolution images that can range from nanometer to millimeter scales. Materials characterization using X-ray imaging has enabled development of advanced composites that will open up new opportunities to improve manufacturing. In order to deploy reinforced materials, such as ceramic matrix composites (CMC), several structures must be accounted for at all times during tensile or compressive loading experiments (Bale et al. 2012). In this scenario, automation represents a key opportunity to gaining insight from  $\mu$ -CT data by detecting features, such as fibrillar structures (Ushizima et al. 2012, 2014).

In collaboration with DOE imaging facilities, and the Center for Advanced Mathematics for Energy Research Applications (CAMERA) (Donatelli et al. 2015), we have developed **FibriPy**, a python-based (Python Software Foundation 1991) computer-aided fiber detector, tracker and analyzer designed to recognize patterns from 3D imagery. **FibriPy** is a software environment that combines user-friendly dashboards with programmable functions to support the analysis automation of 3D  $\mu$ -CT stacks. **FibriPy** complements and extends our previous works on this endeavor, such as the development of pattern recognition and machine learning techniques,

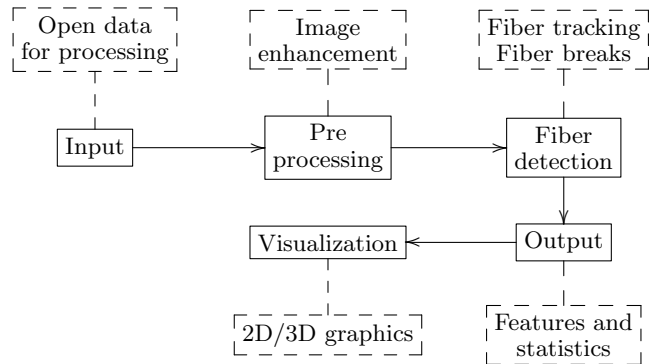


Figure 1: Main steps included in **FibriPy**'s pipeline.

such as statistical region merging and Markov random fields, allied with high performance techniques, helping scientists to explore and understand complex data coming from different sources (Ushizima et al. 2016).

**FibriPy** builds upon **F3D**, an open-source Fiji plugin designed for high-resolution 3D non-linear filtering written in OpenCL (Ushizima et al. 2014) and statistical based techniques for image classification, which are the basis for obtaining measurements that map to physical properties of material samples (Perciano et al. 2016).

The following section describes the main features provided by **FibriPy**. We also give a general overview and comparison with existing software. Section 3 presents examples of the usage of the proposed software and some of the features provided. In Section 4 we draw our conclusions and describe future work.

## 2 Methods in FibriPy

### 2.1 Proposed framework

**FibriPy** is a python-based interactive end-to-end computational pipeline consisting of five main steps as illustrated in Figure 1:

1. *Input* - loads a sequence of image files (BMP, EPS, JPEG, PNG, PPM, TIFF) or a TIFF stack representing slices through a 3D volume;
2. *Preprocessing* - feature and image enhancement using a priori information about the input data, e.g., fiber diameter and image resolution;
3. *Fiber detection and tracking* - detection of fibers

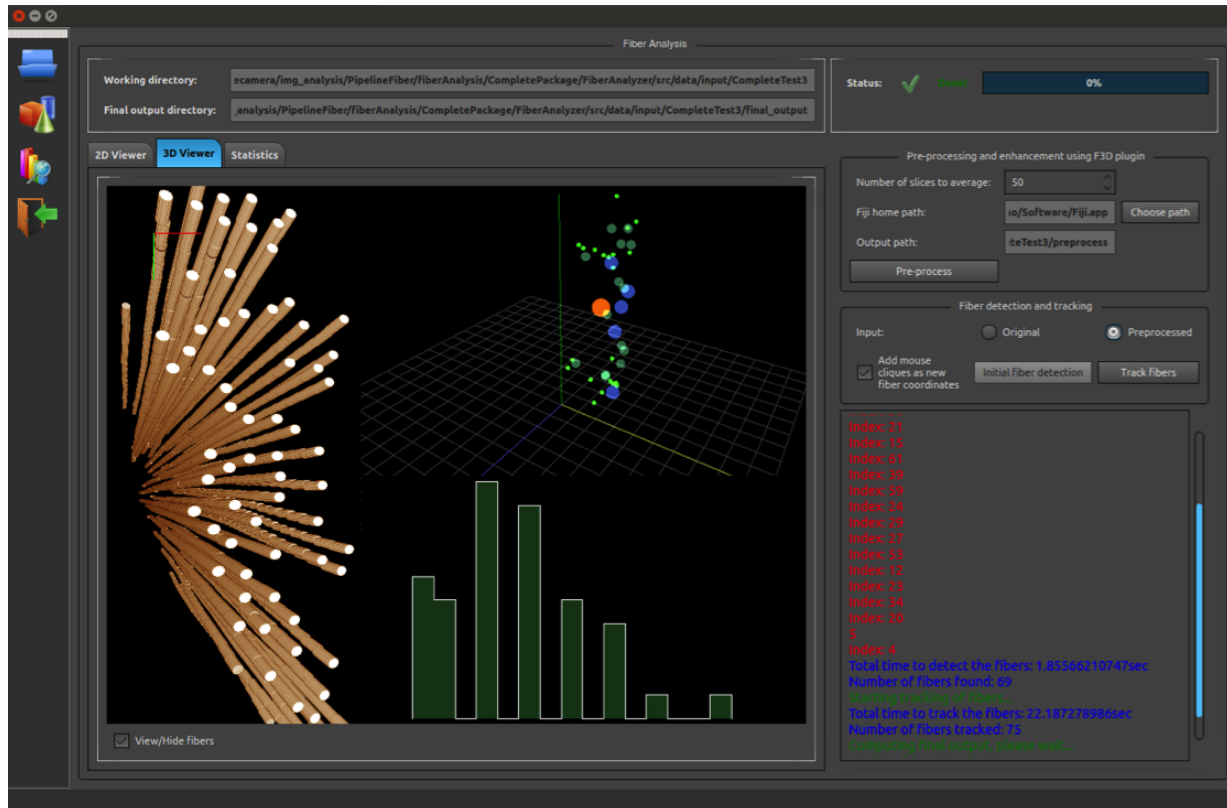


Figure 2: FibriPy GUI illustrating processed  $\mu$ -CT data containing fibers and fiber breaks. 3D rendering, 3D scatterplot of fiber breaks and volume histogram are among the available tools provided by this software.

and fiber breaks throughout the 3D image stack using new computer vision algorithms;

4. *Output* - binary images of segmented features, and quantitative statistical information about the detected fiber breaks;
5. *Visualization* - outputs are represented as 3D renderings and 2D graphics.

The pipeline is accessible through a Graphical User Interface (GUI) at the core of FibriPy, providing high flexibility for the user to access the tools for detection, tracking and analysis of fibers, along with different visualization and analytic tools. Although the analysis can run fully automatically, FibriPy allows user interaction throughout the execution pipeline to tailor parameters for improved accuracy.

FibriPy has been developed and tested to detect fibers and fiber deformations in 3D  $\mu$ -CT images, though it could be applied to other experimental techniques such as scanning transmission electron microscopy. As scalability is one of the main issues when analyzing high-resolution 3D images, FibriPy delivers process-based concurrency and scalable GPU-based visualization, with portability benefits brought by well-established Python packages. The FibriPy framework provides tools for image enhancement, automatic detection of fiber cross-

sections, interactive tools to improve fiber detection, automatic fiber tracking (e.g., connection of detected fiber cross-sections), and 2D/3D visualization. The main contributions are: (a) advanced algorithms for image analysis and feature extraction, such as: structure-based image enhancement using nonlinear filtering, adaptive feature-based matching and learning, and motion tracking based on cross-correlation, (b) Python-centric multi-threading software architecture and (c) GPU-accelerated visualization tools.

## 2.2 Related software tools

A variety of software tools have been developed aiming for the detection and analysis of fibrillar structures in 2D/3D images. Table 1 presents a summary of available algorithms within standard software tools for image analysis, such as Avizo (FEI Corporate 2003), Fiji (Schindelin et al. 2012) and Matlab (Mathworks 1984).

Algorithms in FibriPy aim to overcome some of the issues among the available softwares for fibrillar structures analysis; for example, users have reported the following limitations: (1) Segmentation algorithms are restricted to images with high intensity contrast among phases; (2) Software is tailored to specific images modalities or restricted to 2D images; (3) There is poor scal-

Software/Tool	Characteristics
Avizo	<ul style="list-style-type: none"> <li>- Provides tools for fiber detection</li> <li>- Segmentation capabilities are seldom enough for samples with low contrast and challenging fiber architectures</li> </ul>
BoneJ	<ul style="list-style-type: none"> <li>- Bone image analysis</li> <li>- Works on <math>\mu</math>-CT data but not applicable for the detection of fibrillar structures</li> </ul>
DiameterJ	<ul style="list-style-type: none"> <li>- Analysis of nanofiber diameter from scanning electron microscope (SEM) micrographs</li> <li>- Applied only to 2D images</li> <li>- Detection of structures under low contrast conditions is restricted</li> </ul>
Fiji	
FibrilTool	<ul style="list-style-type: none"> <li>- Quantifies fibrillar structures in raw microscopy images</li> <li>- Applied only to 2D images</li> </ul>
Ttorg	<ul style="list-style-type: none"> <li>- Analysis of transverse tubular system in confocal microscopy images</li> <li>- Tools is not applicable for the detection of other types of fibrillar structures</li> </ul>
TubeSess	<ul style="list-style-type: none"> <li>- Calculates a “tube-like” score for each point of an image</li> <li>- Used mainly to segment structures such as blood vessels and neurons</li> <li>- Analysis of samples with more than 100GB is unfeasible</li> </ul>
Matlab	<ul style="list-style-type: none"> <li>- Scripts to detect fiber-like structures exist</li> <li>- Precision of detection decreases drastically for samples with low contrast</li> <li>- Analysis of samples with more than 100GB is unfeasible</li> </ul>

Table 1: Existing software tools for fibrillar structures analysis.

ability of methods, i.e., analysis of large high-resolution data is not feasible.

### 3 Experiments

Figure 2 illustrates **FibriPy** being used to analyze a sample with solid fibers embedded in a matrix. It presents the results of the detection of fibers and fiber breaks, the 3D volume rendering of the fibers and fibers breaks, the 3D scatterplot of fiber breaks, and the volume histogram of fiber breaks. These exploratory tools translate different metrics, obtained throughout the fiber detection process, into visualizations. The current metrics set in **FibriPy** includes: (a) number of fibers, (b) fiber density across the sample, (c) fiber break locations within the volume, (d) fiber break distribution throughout the sample, (e) porosity and (f) non-uniformity (Shou et al. 2015). This metric set is essential to understand sample failure from a microstructure point of view during tensile or compressive loading experiments, and they support the development of more efficient and resistant materials.

Figure 3 presents the 3D rendering of detected solid fibers and fiber breaks in details. This tool allows the user to visualize fibers and fibers breaks jointly or separately, and provides a variety of options to change points of view, camera position, zooming, transparency and texture.

Based on the detection of fibers and fiber breaks, **FibriPy** can extract all the metrics mentioned previously in order to provide different graphics for the user to quickly visualize sample properties, such as the 3D



Figure 3: 3D rendering of solid fibers detected from a composite sample, along with detected fiber failures (gaps).

scatterplot of fiber breaks illustrated in Figure 4. The graphic shows the distribution of the fiber breaks in the analyzed samples, showing information about the position of the failures and volume. Additionally, fiber breaks can be grouped visually by color and size based on volume ranges.

### 4 Conclusions

This paper introduces **FibriPy**, a scalable and portable software environment for the analysis of fibrillar structures in 3D image stacks. Experiments related to the development of advanced composites rely on the de-

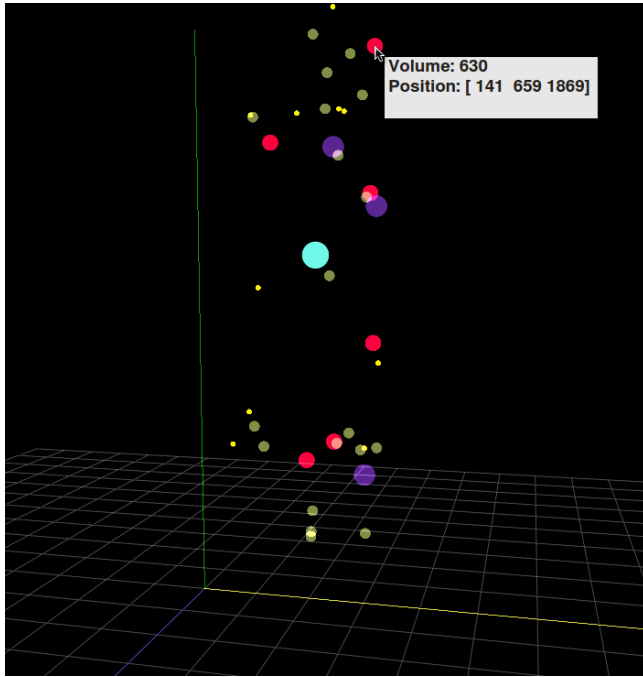


Figure 4: 3D scatterplot graphic showing position of the fibers in the sample and volumes.

tection of sample features such as fibers. This is an important step towards the analysis of sample structure and consequently, affects manufacturing processes reliant on such materials. In spite of the high demand for the analysis of fibrillar structures across different science domains, there is a lack of computational tools capable of performing this task, specially when dealing with high resolution datasets carrying multiscale information - *FibriPy* comes to fill in this gap. This work reports on preliminary accomplishments towards automated analysis and understanding of material samples, particularly those acquired at high-throughput and dependent on automatic identification of micro-damage.

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## References

Bale, H. A., Haboub, A., Macdowell, A. A., Nasiatka, J. R., Parkinson, D. Y., Cox, B. N., Marshall, D. B. & Ritchie, R. O. (2012), ‘Real-time quantitative imaging

of failure events in materials under load at temperatures above 1,600C.’, *Nat Mater* **12**, 40–46.

Donatelli, J. et al. (2015), ‘Camera: The center for advanced mathematics for energy research applications’, *Synchrotron Radiation News* **28**(2), 4–9.

FEI Corporate (2003), ‘Avizo 3D Software’, <http://www.fei.com/software/avizo-3d/>. Online; accessed 24 March 2017.

MacDowell, A. A., Parkinson, D. Y., Haboub, A., Schaible, E., Nasiatka, J. R., Yee, C. A., Jameson, J. R., Ajo-Franklin, J. B., Brodersen, C. R. & McElrone, A. J. (2012), ‘X-ray micro-tomography at the advanced light source’.

Mathworks (1984), ‘Matlab’, <http://mathworks.com/products/matlab>. Online; accessed 24 March 2017.

Perciano, T., Ushizima, D. M., Bethel, E. W., Mizrahi, Y. D., Parkinson, D. & Sethian, J. A. (2016), Reduced-complexity image segmentation under parallel markov random field formulation using graph partitioning, in ‘2016 IEEE International Conference on Image Processing (ICIP)’, pp. 1259–1263.

Python Software Foundation (1991), ‘Python programming language’, <http://www.python.org>. Online; accessed 24 March 2017.

Schindelin, J., Arganda-Carreras, I., Frise, E., Kaynig, V., Longair, M., Pietzsch, T., Preibisch, S., Rueden, C., Saalfeld, S., Schmid, B., Tinevez, J.-Y., White, D. J., Hartenstein, V., Eliceiri, K., Tomancak, P. & Cardona, A. (2012), ‘Fiji: an open-source platform for biological-image analysis’, *Nat Meth* **9**(7), 676–682.

Shou, D., Ye, L. & Fan, J. (2015), ‘On the longitudinal permeability of aligned fiber arrays’, *Journal of Composite Materials* **49**(14), 1753–1763.

Ushizima, D. M., Bale, H. A., Bethel, E. W., Ercius, P., Helms, B. A., Krishnan, H., Grinberg, L. T., Haranczyk, M., Macdowell, A. A., Odziomek, K., Parkinson, D. Y., Perciano, T., Ritchie, R. O. & Yang, C. (2016), ‘IDEAL: Images Across Domains, Experiments, Algorithms and Learning’, *JOM* **68**(11), 2963–2972.

Ushizima, D. M., Perciano, T., Krishnan, H., Loring, B., Bale, H., Parkinson, D. & Sethian, J. (2014), ‘Structure recognition from high resolution images of ceramic composites’, *IEEE International Conference on Big Data*.

Ushizima, D., Morozov, D., Weber, G. H., Bianchi, A. G. C., Sethian, J. A. & Bethel, E. W. (2012), ‘Augmented topological descriptors of pore networks for material science’, *IEEE Transactions on Visualization and Computer Graphics* **18**(12), 2041–2050.