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Model-Based Super-Resolution of SEM Images of Nano-Materials

Suhas Sreehari[1], S. V. Venkatakrishnan[2], Jeff Simmons[3], Lawrence Drummy[3], and Charles A. Bouman[1].

[1.] Electrical and Computer Engineering, Purdue University, West Lafayette, IN, USA.
[2.] Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley, CA, USA.
[3.] Air Force Research Laboratory, Dayton, OH, USA.

Many imaging problems in materials and biological sciences involve reconstruction of high-resolution images from low-resolution SEM images that contain several similar or identical non-local structures. Such SEM images can be sparsely represented owing to the enormous redundancy caused by repeating structures. Model-based iterative reconstruction (MBIR) is a powerful iterative reconstruction framework that could theoretically exploit such redundancies [1]. However, in practice, determining a prior probability term in the maximum *a* posteriori cost function that accounts for the similarity between non-local structures remains an open problem. Meanwhile, non-local patch-based denoising algorithms like non-local means (NLM) have been known to exploit non-local similarities in images. In fact, there have been several efforts to solve the super-resolution problem using patch-based models, dictionary learning and example-based methods [2]. In any case, it is unclear how to use NLM-based denoising algorithms as prior models within the MBIR framework.

In this paper, we present a novel solution to the problem of super-resolution that works by using high-resolution patches from an external library. Our library-based non-local means (LB-NLM) algorithm contrasts the standard NLM in the quality and resolution of the patches that are weighted. The images interpolated to the desired higher resolution using LB-NLM are found to have lower mean squared error compared to linear methods like Shepard's interpolation, as well as solutions that use standard NLM. Additionally, the LB-NLM interpolated images are sharper, have textures visually consistent with ground truth images, and more accurate edge features. More importantly, our interpolated images lack resilient artifacts like *jaggies* that often manifest in super-resolution by factors around 4x. The key step in our proposed solution is the use of LB-NLM as a prior model in our model-based regularized inversion framework. This ordinarily challenging step is performed easily using the plug-and-play (P&P) framework [3] that is based on the alternating direction method of multipliers (ADMM) [4]. The main benefit of the plug-and-play framework is the decoupling of the forward and prior models of the MAP cost function. The forward model for this problem is given simply by the assumed point-spread function (PSF) of the electron microscope, while LB-NLM serves as the prior model.

In Figures 1 and 2, we present 4x super-resolution results on a scanning electron microscope image and a surface crack in the shell of marine mollusk, *Hinea brasiliana*. Along with the claims made above, we also show that a variety of denoising algorithms such as DSG-NLM [3] and library-based NLM (LB-NLM) can be plugged in as prior models using the P&P framework. To implement the LB-NLM, we extracted 10,000 5×5 patches from the "library images" (see Fig. 1, top left) to form the patch library. We did not add any noise to the measurements. The P&P super-resolution algorithm with LB-NLM as the prior produced the best quality interpolated images with the lowest mean squared error, visually accurate textures and edge-features, and no jaggies. Our results demonstrate that using an external library of high quality patches within the flexible P&P framework can improve super-resolution quality much beyond traditional model-based as well as linear interpolation methods.

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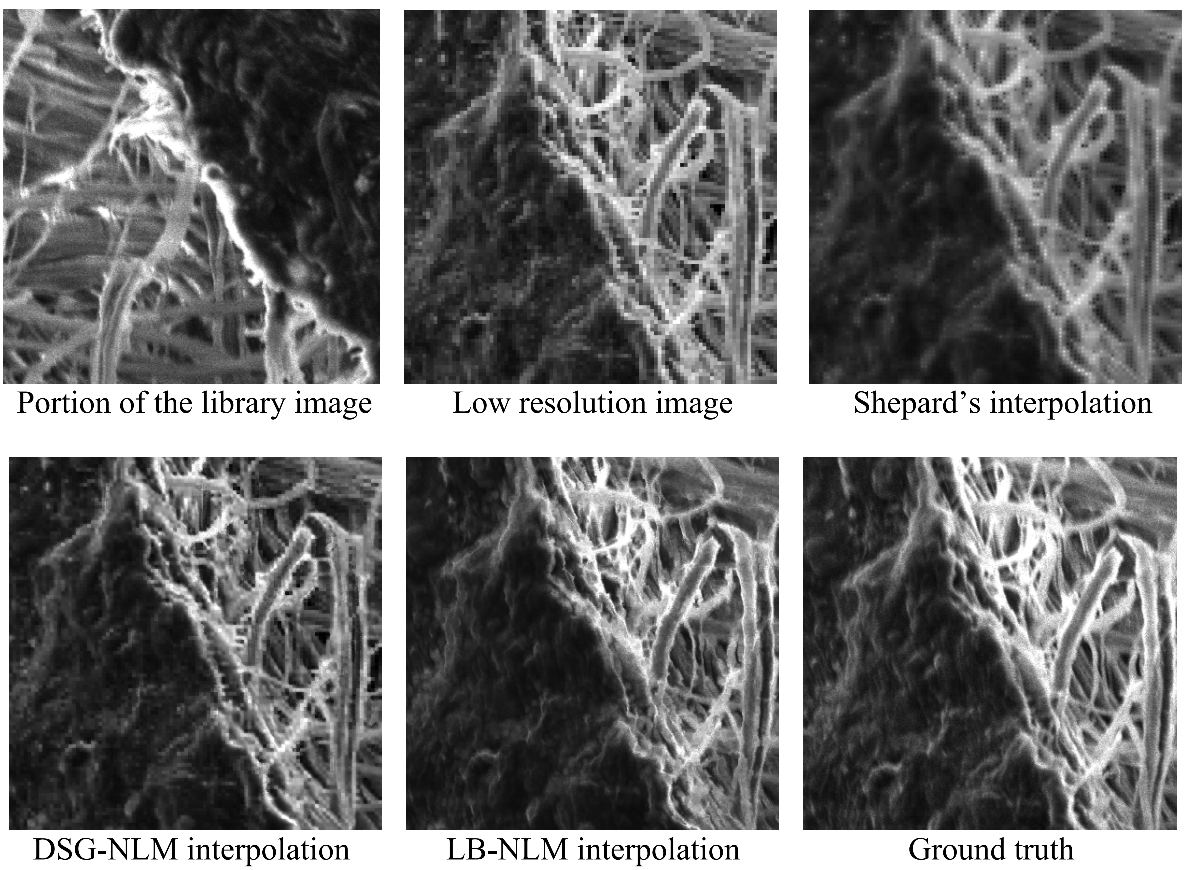

Figure 1. 4x super-resolution of a 100×100 SEM image of surface crack in the shell of the marine mollusk *Hinea brasiliana*.

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